INTERNATIONAL JOURNAL OF
IJCOE
COASTAL, OFFSHORE & ENVIRONMENTAL ENGINEERING

Effects of Hybrid Fiber on Flexural Behavior of Green RC Beams in Oman Sea
Hamed Safayenikoo

Damage localization and quantification in the Catwalk of Foroozan offshore complex using improved modal strain energy method
Mehdi Alavinezhad; Madjid Ghodsi Hassanabad; Mohammad Javad Ketabdari; Masood Nekooei

Rationality for Engineers: Part I- Setting the scene
Sirous Yasseri

Application of Fuzzy Cognitive Map to Design the Causal Structure and Analyze the Factors Affecting Good Governance in the Ports and Maritime Organization
Ahmad Ghafarzadeh; Gholamreza Memarzadeh Tehran; Naser Hamidi; Nabiollah Mohammadi

Integration of geographical information system and Wave Hindcast model - case study: Persian Gulf
Masoud Moradi

Dynamic Stability Analysis of High-Speed Trains Moving over Sea-Cross Bridge subjected to Rail Irregularities
Amin Razzaghi Kalajahi; Morteza Esmaeili; Jabbar Ali Zakeri

Volume 6 | Issue 2 | May 2021

www.ijcoe.org info@ijcoe.org

www.ijcoe.org

International Journal of Coastal, Offshore and Environmental Engineering (IJCOE)
Vol. 6/ Issue. 2 / May 2021
22

International Journal of Coastal, Offshore & Environmental Engineering

Since 2015

ISSN: 2980-8731 (online)

Volume 6 | Issue 2 | May 2021

IJCOE

Editor-in-Chief: Prof. Hamid S.Bahai

International Journal of Coastal, Offshore & Environmental Engineering
ISSN: 2980-8731 (online)
Since 2015

In The Name of God

Message from the Editor-in-Chief

The IJCOE journal office was established in 2015,and its first issue was published in 2016. TheIJCOE covers a wide range of research in thefields of oceanography & ocean technology, aswell as marine industries & marine engineering.The editorial board of IJCOE consists of nearly130 of the greatest scientists and researchersfrom over 30 countries worldwide, and thejournal's review board comprises 1,000 membersfrom all five continents. The membership andapplication process for joining the editorial andreview boards of this journal is ongoing. IJCOE isa research-academic quarterly journal that haspublication and distribution permissions fromthe Press Organization and permission topublish scientific-research articles from theMinistry of Science, Research, and Technology(MSRT) with an "A" rating. It also holds a "Q1"rating from the ISC institute with an impactfactor (IF) of approximately 0.43 and isconsidered a "core journal" (prestigious andoutstanding journal). IJCOE is an open-accessjournal and allows the download and receipt ofaccepted articles in full text for free. It respectsand adheres to copyright and COPE regulations.The journal's office operates 24/7, providingservices to researchers. In addition to publishinga regular quarterly journal, IJCOE has 16 specialissues on specific topics in preparation. It alsoprovides conditions for publishing specializedbooks, references, and handbooks. Moreover, itis ready to cooperate with the secretariats ofreputable international conferences to publishtheir selected and outstanding articles. IJCOEevaluates, appraises, and publishes books,articles, and the scientific achievements andfindings of esteemed researchers and scientistsworldwide who are innovating and conductingin-depth research in the "important and strategicfield of the maritime technology & Oceanengineering." It welcomes any form of jointcooperation with universities, research institutes,and related research centers at the national,regional, and international levels, and extends ahand for collaboration.

Classification of Editorial Board in IJCOE

- Editor-in-Chief
- Director-in-Chief
- Deputy Editor
- Executive Managers
- English Text Editor
- Technical Editor
- International Editorial Board
- National Editorial Board
- Editorial Board Associate
- Editorial Board Assistant
- Guest Editorial Board
- Advisory Board
- Administrative Coordinator
- Honorary Board Member
- Methodology Advisor

Author Benefits

- Open Access
- Rapid Publication
- Thorough Peer-Review
- No Copyright Constraints
- Coverage by Leading Indexing Services
- Discounts On Article Processing Charges (APC)
- No Space Constraints, No restriction on the maximum length of the papers, number of figures or colors

INTERNATIONAL JOURNAL OF IJCOE COASTAL, OFFSHORE & ENVIRONMENTAL ENGINEERING

Aims of IJCOE

Hydrodynamics

Marine equipment

Structural mechanics

Ocean environmental predictions

Stochastic calculations Experimental

Automatic Control of Marine Systems

Scope of IJCOE

Marine Hazards

Ocean Acoustics

Naval Architecture

Ocean Engineering

Coastal Engineering

Marine Meteorology

Marine Earth Sciences

Underwater Technology

Marine Renewable Energy

Polar & Arctic Engineering

Marine Renewable Energy

Marine Geography & Geodesy

Marine Environmental Engineering

Automatic Control of Marine Systems

Hydro Physics & Physical Oceanography

Type of papers

- Case Studies
- Book Reviews
- Review Article
- Letters to the Editor
- Methodology Papers
- Editorials and Commentaries
- Response or Rejoinder Papers
- Perspective or Opinion Papers
- Conceptual or Theoretical Papers
- Meta-Analysis and Systematic Reviews
- Short Communications or Brief Reports
- Research Articles (Original Research Papers)

Scientific Research Journal

Ministry of Science, Research And Technology (MSRT)

Jurnal Ranking 2023: A

Ministry Of Science, Research And Technology (ISC)

Citation Impact 2022: 0.429

Quartile 2022 : Q1

Core Collection

INTERNATIONAL JOURNAL OF IJCOE COASTAL, OFFSHORE & ENVIRONMENTAL ENGINEERING

IJCOE is a Member of

CIVILICA | Google Scholar | Jouroscope
COPE | ISC | REF.IR
DOAJ | ISSN | Researcher.Life
doi Crossref mEDRA | iThenticate | magiran
Open Access | pistotn | ResearchGate
Regional Information Center for Science and Technology RICEST | ScienceGate | Scilit
SID | website.informer.com | WEBrate

Cantact Us

Office 1 | Research Institute of Meteorology and Atmospheric Science

Address | Tehran, Shahid Kharrazi Highway, Pajoohesh Blvd, Research Institute of Meteorology and Atmospheric Science, Sand and Dust Storm International Research Center (SDS-IRC), No. 13, 1st floor.

Phone | +982144787652

Postal code | 13611-14977

website | www.rimac.ac.ir

Office 2 | Iranian National Institute for Oceanography and Atmospheric Science

Address | Tehran, Dr. Fatemi Gharbi St., Shahid Etemadzade St., No. 3, third floor.

Phone | +982166944873

Postal code | 13389 – 14118

website | www.inio.ac.ir

Email | Info@ijcoe.org

Website | www.ijcoe.org

Follow Us

www.ijcoe.org

INTERNATIONAL JOURNAL OF IJCOE COASTAL, OFFSHORE & ENVIRONMENTAL ENGINEERING

Volume & Issue:

Volume 6, Issue 2, May 2021

Number of Articles: 6

Content

Effects of Hybrid Fiber on Flexural Behavior of Green RC Beams in Oman Sea 1
Hamed Safayenikoo

Damage localization and quantification in the Catwalk of Foroozan offshore complex using improved modal strain energy method 11
Mehdi Alavinezhad; Madjid Ghodsi Hassanabad; Mohammad Javad Ketabdari; Masood Nekooei

Rationality for Engineers: Part I- Setting the scene 22
Sirous Yasseri

Application of Fuzzy Cognitive Map to Design the Causal Structure and Analyze the Factors Affecting Good Governance in the Ports and Maritime Organization 34
Ahmad Ghafarzadeh; Gholamreza Memarzadeh Tehran; Naser Hamidi; Nabiollah Mohammadi

Integration of geographical information system and Wave Hindcast model - case study: Persian Gulf 47
Masoud Moradi

Dynamic Stability Analysis of High-Speed Trains Moving over Sea-Cross Bridge subjected to Rail Irregularities 56
Amin Razzaghi Kalajahi; Morteza Esmaeili; Jabbar Ali Zakeri

INTERNATIONAL JOURNAL OF
COASTAL & OFFSHORE ENGINEERING

IJCOE Vol.6/No. 2/Spring 2021 (1-10)

Available online at: www. Ijcoe.org

Effects of Hybrid Fiber on Flexural Behavior of Green RC Beams in Oman Sea

Hamed Safayenikoo

[1] *Faculty member, Chabahar Maritime University; h.safayenikoo@cmu.ac.ir*

ARTICLE INFO

Article History:
Received: 15 Jan. 2021
Accepted: 27 Apr. 2021

Keywords:
Marine tidal zone
Glass fiber
Polypropylene fiber
Steel fiber
Toughness

ABSTRACT

Steel rebar corrosion because of the cracks in marine reinforced concrete (RC) structures is the main type of deterioration that leads to decrease the load-carrying capacity, ductility, and service life. The use of different fibers such as steel fiber (SF), glass fiber (GF), and polypropylene fiber (PF) in RC beams can reduce the cracks and increase the load-bearing capacity and toughness of RC beams. Moreover, it seems that RC beams containing hybrid of SF, GF, and PF have been higher flexural capacity and toughness rather than RC composites with only one type of fiber. However, the role of mono or hybrid fiber will be depended on environmental conditions. Consequently, load-bearing capacity and toughness of Green RC beam with 15% metakaolin (MK) as a cement replacement, containing SF, PF, GF, (S+P)F, and (S+G)F as fibers, at 28, 90, and 180 days in tidal zone of Oman Sea were determined. The dimension of the beams was 200×200×750 mm. The fibers included macro and microfibers. Macro fiber was steel with 50 mm length. Microfibers were GF and PF with 12 mm length. Results indicated that by the addition of PF, GF, SF, (S+P)F, and (S+G)F to RC beams the load-bearing capacity and toughness are increased up to 41%. Meanwhile, the hybrid effect of fiber was more than the mono one.

1. Introduction

Sustainable advantages of concrete and cement in CO_2 emission and energy consumption have been affected by the high volume utilization of concrete. The use of ordinary Portland cement (OPC) in concrete leads to about 8 and 3% of CO_2 emissions and the world's energy consumption, respectively [1][2]. On the other hand, SO_3 and NO_x considered too as greenhouse are released from cement manufactures [3][4]. Therefore, green concrete and generating less pollution are essential for concrete production. Indeed, compared to OPC, green concrete is defined as concrete that has less energy consumption and carbon dioxide emission. Against this background, the use of cementitious replacement materials will help to reduce environmental pollution by replacing part of cement in concrete and green concrete production. MK as a cement replacement is known to be a highly pozzolanic material. MK has a positive environmental impact and can improve concrete mechanical behavior. It reacts with hydrated cement and can reduce the concrete porosity and enhance the concrete durability [5].

Besides, the durability of concrete depends on its environmental conditions. Although marine environments are considered as a positive capacity for the transport industry, damage or deterioration of marine concrete structures is one of the main problems in this environment. Normally, marine concrete structures are divided into three zones. The first section, above the high tide line, is directly exposed to atmospheric air containing sea salts. In this part, cracking due to steel reinforcement corrosion and chemical reactions happens. The next part, between the high-tide and low-tide lines (tidal zone), is exposed to cracking, spalling, steel corrosion, material degradation, and physical damage. The last zone, which is situated below the low-tide all the time, is susceptible to material loss from the reaction of aggressive ions within the seawater [6]. Aggressive ions such as NaCl, $MgCl_2$, $MgSO_4$, $CaSO_4$, and K_2SO_4 penetrate marine structures when cracking is occurred in concrete. Cracking by facilitating chloride penetration and other harmful ions can cause reduce the serviceability life, durability, and flexural capacity of concrete structures [7]. Therefore, any factor that reduces cracks can help to increase the bearing capacity, ductility, and durability of concrete structures in the sea environment.

Cracks at both micro and macro-levels can be limited by using fibers as reinforcement. At the micro-level, the initiation and growth of cracks will be limited. Moreover, at the macro-level, fibers will improve toughness and ductility by effective bridging and preventing cracks from unstable propagation. Hybrid fiber composites made by combining organic PF, inorganic GF, and SF have higher ductility and fracture toughness rather OPC or mono fiber composites. It seems that control of the micro-cracks and their growth in hybrid reinforced concrete is provided by small or soft fiber. Also, the second fiber (long or strong) arrest the propagation of macro-cracks and enhance the toughness of the composite. In another word, early age properties such as plastic shrinkage will be improved by small or soft fiber and mechanical properties will be enhanced by long or strong one [8][9][10][11].

The usage of fibers in RC has been evaluated by many researchers [12]. It has been found that shear, tensile strength, and fracture toughness will be improved by fibers addition to concrete. Glavind et al. [13] found that hybridization of SF and PF increases the ultimate compressive strain of concrete. Larsen et al. [14] tasted SF and PF hybrids on fracture energy of cementitious composites. They reported that fracture energy after 10 years in out-door exposure increases 40%. Bentur et al. [15] studied the effect of combined SF and PF concluded that the ultimate strength of composites is dependent on stronger and stiffer fiber while toughness and strain capacity are related to flexible and ductile fiber.

Banthia et al. [16] showed that composites reinforced with hybrids of PF and mesophase carbon fiber (CF) have the highest level of synergy in toughness. Mihashi et al. [17] found that hybrid fiber composites containing polyethylene (PEF) and SF show excellent performance against corrosion compared to mono fiber-reinforced composites. Caggiano et al. [18] tasted hybridization of SF and PF in cement composites. They concluded that post-cracking behavior is higher for hybrid fiber reinforced concrete rather than mono fiber composites. Huang et al. [19][20] reported that (S-P)F-RC specimens containing hybrid fiber have better bond strength in terms of peak bond strength and corresponding slip compared to mono fiber composites. Won et al., Yoo et al. and Li et al. [21][22][23] found that by the addition of fibers, the peak bond strength has a rise in slip.

Gali et al. [24] found that the early fracture response of hybrid fiber concrete is better than SF reinforced concrete. Sadrinejad et al. [25] studied the influence of hybrid fibers on serviceability of RC beams containing SF, Polyolefin (POF), and PF. they concluded that corrosion level of bars is reduced by the presence of fibers. Liu et al. [26] conducted chloride ion diffusion in concrete containing PF and GF. The results showed that chloride penetration in concrete is dependent on fiber diameter, the volume fraction of fibers, aggregate diameter, and volume fraction. Prathipati et al. [27] indicated that concrete containing hybrid GF and SF has higher distribution characteristics than mono fiber composites.

According to the above literature study, very few researches about the flexural performance of reinforced green concrete containing hybrid SF, GF, and PF in marine environments have been done. The aim of performed experimental tests, in this paper, is to study the flexural behavior of ordinary reinforced green concrete (RC) containing SF, PF, GF, hybrid SF and PF [(S+P)F] or hybrid SF and GF [(S+G)F] in the tidal zone of Oman Sea. Toughness and maximum force in force-deflection diagrams till 15 mm deflection are compared [28]. Considering the above paragraph, in this study, MK as a cement replacement is selected for green concrete.

2. Materials and methods

Ordinary Portland cement Type II and coarse aggregate with a maximum size of 19 mm were used in the present study. To remove dust and other fines the coarse aggregate was washed. It was graded based on ASTM C 33. The fineness modulus of sand and the sizes were 2.5 and 0 to 4 mm, respectively. Naphthalene Sulfonate Formaldehyde (NSF) as a Super-Plasticizer (SP) was mixed to get the required workability in concrete. MK as a cement replacement was added by 15% of the weight to cementitious materials. The water to cement ratio was 0.4. The style of concrete mixes was weight basis. The mineralogical composition of Portland cement, MK, and aggregates is shown in Table 1. Mixture identification and fiber types are indicated in Table 2. According to Table 2, for example, (R+P)C means RC beams containing mono PF, or (R+S+P)C indicates RC beams containing hybrid PF and SF. On the other hand, the total fiber volume fraction for all the mixes was 1%. The physical properties of fibers are given in Table 3. The fibers included macro and microfibers. Macro fiber was steel with 50 mm length.

Table 1 Chemical properties of the cement and MK

Chemical composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	L.O.I	Na_2O	K_2O	Other
Cement (Weight ratio %)	21.9	4.6	3.9	64.5	2.6	0.8	0.3	0.9	0.5
MK (Weight ratio %)	53.2	44.54	0.82	0.08	0.04	0.9	0.2	0.04	0.18
Gravel	7.9	0.6	1.1	44.1	4.6	40.9	0.2	0.2	0.4
Sand	51.9	5.8	7.6	16.1	7.8	8.1	1.2	0.9	0.6

Table 2 Mixture identification and fiber types

Mix ID	Type of mix	Volume of various fiber types (%)			Total Vf
		PF	GF	SF	
RC	Plain	0.0	0.0	0.0	1.0
(R+P)C	Single fiber	1.0	0.0	0.0	1.0
(R+G)C	Single fiber	0.0	1.0	0.0	1.0
(R+S)C	Single fiber	0.0	0.0	1.0	1.0
(R+S+P)C	Hybrid fiber	0.1	0.0	0.9	1.0
(R+S+G)C	Hybrid fiber	0.0	0.1	0.9	1.0

Microfibers were glass and polypropylene with 12 mm length (Figure 1). The type of GF is alkali resistance RC beams have the same reinforcement details, four 10 mm diameter bars were used at beam bottom and top. 6 mm diameter stirrups at 65 mm.

Table 3 Physical Properties of fibers

Property	SF	PF	GF
Length (mm)	50	12	12
Diameter (mm)	0.55	0.022	0.014
Aspect Ratio	91	545	857
Elastic Modulus (GPa)	200	3.5-10	70-80
Tensile Strength (MPa)	1100	400-600	1400-1700

(AR). Fifty-four RC beams were cast and loaded under two points, using different percentages of fibers. The size of the beams was 200 × 200 × 750 mm.

(a) (b) (c)

Figure 1. Fibers are used in beams.

(a:) Steel Fiber, (b): Polypropylene Fiber, (c): Glass Fiber

RC beams have the same reinforcement details, four 10 mm diameter bars were used at beam bottom and top. 6 mm diameter stirrups at 65 mm. The reinforcement ratio was about 0.6%. The cover thickness for longitudinal and transverse reinforcement was 55 mm. The longitudinal and transverse reinforcements had a nominal yield strength of 400 MPa (Figure 2). Four-point loading was applied, producing a constant moment region of 210 mm in the middle of a 650 mm clear span. Loading was monotonically applied with a maximum capacity of 400 KN and the loads and deflections were simultaneously recorded.
The recording rate for mid-span deflections and the load was 1 mm/min. To obtain the net mid-span deflection, the support settlements were subtracted from the measured mid-span deflection by using LVDTs. After casting, specimens were cured at laboratory temperature for 28 days and carried to Oman Sea tidal zone (Figures 3 and 4). The temperature in the Oman Sea was (20-27) ▫C and the PH value was 7.66. The average compressive strength for 6 beams mixtures is 24 MPa, approximately.

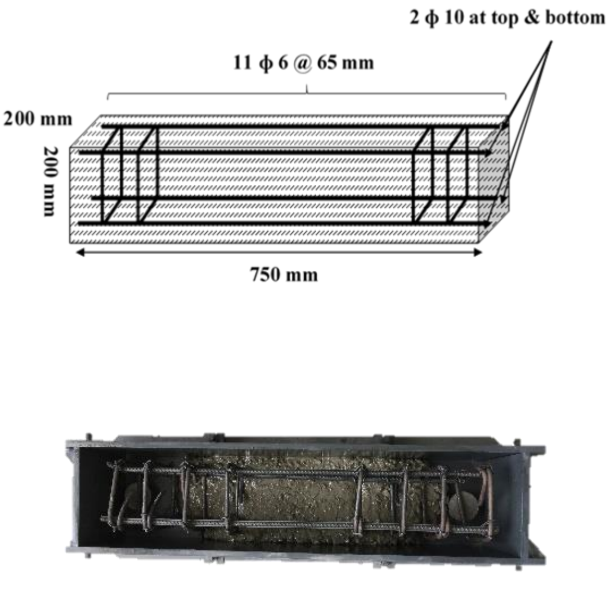


Figure 2. Details of tested beam reinforcement containing transverse and longitudinal reinforcement

Figure 3. Beam specimens in Oman Sea environment

Figure 4. Tidal zone in Oman Sea environment

3. Result and Discussion

The measured values were load and deflections and the calculated parameters were the max of bearing force and fracture toughness at 28, 90, and 180 days. Generally, the load-deflection diagram up to the specific deflection such as its maximum is named toughness. The toughness is an energy absorption capacity criteria for the flexural behavior of beams [29]. Achieve maximum deflection for calculating toughness of RC beams containing fiber is not easy. Therefore, in this paper, the maximum deflection was selected 15 mm for calculating the toughness, for all beams.

3.1. Effect of mono PF, GF, and SF on the toughness of green RC beams in Oman Sea tidal zone

Figure 5 shows the load-deflection diagrams for RC and (R+P)C beams at 28, 90, and 180 days in the Oman Sea tidal zone.

According to Figure 5, (R+P)C has 14 to18% higher force bearing capacity than RC beams in marine tidal zone till 180 days. On the other hand, toughness by adding PF to RC beams is improved by 10 to 13%. One of the most causes of service life reduction in marine RC structures is corrosion. The bearing capacity of marine structures will be decreased with aging due to reinforcement corrosion through concrete enlargement, cracks

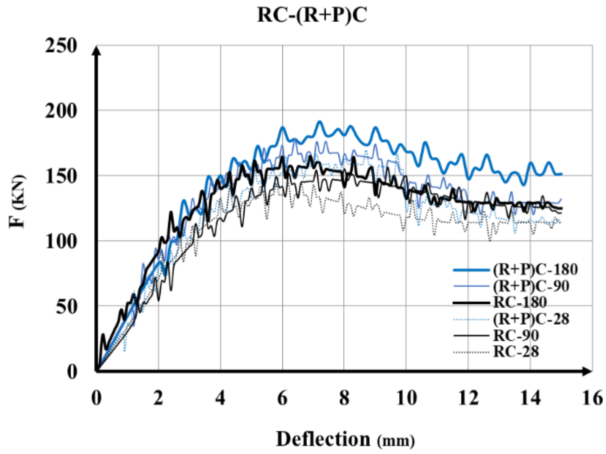


Figure 5. Load-deflection diagrams of RC and (R+P)C beams

the organization, or concrete cover spalling. Subsequently, a cross-section of corroded bars, ultimate strength of elements, and finally, ductility of marine RC structures will be decreased. Nevertheless, the toughness of marine structures by use of PF in RC structures will be increased. This is because of the delay in the corrosion initiation of steel [30][31][32], reduction bond between corroded steel and concrete [33] and prevent the widening of corrosion cracks [34]. Generally, one of the most synthetic fibers with easy dispersion that is made of monomeric C_3H_6, in various mixtures of concrete, is PF. The bold benefits of this fiber are cheap cost, ineffective property at high pH of the cementitious environment, and controlling plastic shrinkage cracking [35][36]. Ductility in RC structures containing fibers can be achieved by two different mechanisms: a) fiber composites can bear the plastic deformation or b) the plastic deformations are provided by bonding interface fiber/paste. In (R+P)C beams, since the fibers have not considerable debonding with round matrix, it seems that the first mechanism is happened [37]. On the other hand and based on the microstructure analysis, it seems that PF makes a network to limit the growth of CH crystalline, and thus, the microvoids, size, and orientation of CH are decreased. As a result, microstructures and the aggregate-cement interfacial transition zone of (R+P)C beams have less porosity and micro-cracking than RC. Also on the macro scale and flexural behavior of the beams, PF holds the concrete component together and resists physical damage and cracking propagation [38]. Moreover, MK through decreasing the porosity, as a cement replacement, helps cement paste to bond with PF, too [9]. Therefore, it seems that role of PF in increasing of bearing force and toughness of RC beams in terms of micro and macrostructures in the marine environment is noticeable.

Considering the load-deflection diagrams, calculated parameters were load carrying capacity and toughness for RC beams with or without mono or hybrid fiber in the Oman Sea tidal zone (Table 4). Figure 6 presents the two samples of concrete containing fiber and rebar after fracture.

Table 4 Maximum force and toughness values

Mix ID	P_{max} (KN)			Toughness (N.m)		
	28 (days)	90 (days)	180 (days)	28 (days)	90 (days)	180 (days)
RC	144.18	156.50	165.12	1617.87	1748.39	1894.58
(R+P)C	169.90	178.28	191.55	1792.12	1956.14	2144.96
(R+G)C	177.30	183.50	193.40	1859.11	1993.92	2158.59
(R+S)C	174.20	184.42	203.12	2003.24	2088.85	2344.15
(R+S+P)C	181.22	192.49	216.25	2082.41	2232.47	2529.64
(R+S+G)C	191.25	205.02	228.25	2213.89	2334.54	2674.79

(a) (b)

Figure 6. Beam specimens at 90 days;

(a): (R+S+G)C, (b): (R+S+G)C

Figure 7 presents the load-deflection diagrams for RC and (R+G)C beams at 28, 90, and 180 days in the Oman Sea tidal zone

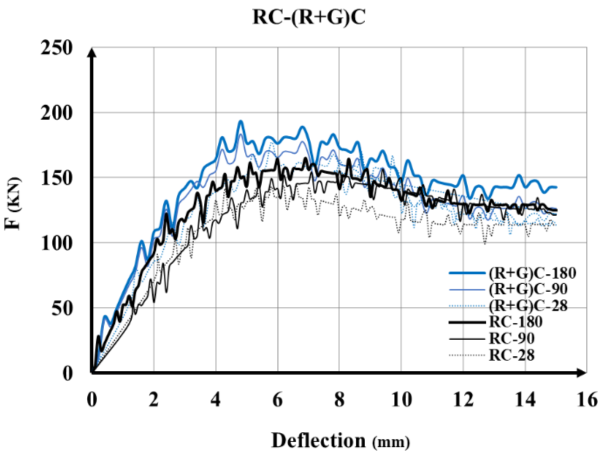


Figure 7. Load-deflection diagrams of RC and (R+G)C beams

As shown in Figure 7, (R+G)C has 17 to 23% higher force bearing capacity than RC beams in marine tidal zone till 180 days. On the other hand, toughness by adding PF to RC beams is improved by 14% approximately. Also load-bearing capacity and toughness of (R+G)C and (R+P)C is not considerable.

Generally, in concrete containing GF, after the hydration process, lime crystals and calcium silicate hydrates (C-S-H) penetrate the fiber bundles. Consequently, spaces between glass filaments are filled and the bond between glass filaments is increased. The result of bonding is embrittlement and lack of fiber ductility with aging [39]. A most beneficial method to prevent the adverse effect of GF in concrete is to use additive materials in combination with AR glass fiber. Among the materials used in cement paste, pozzolanic admixture by chemical reaction with $Ca(OH)_2$ produced in hydration, prevents the accumulation of these materials around the fibers and enhance the flexural behavior of the concrete[40][41][42][43]. Therefore, MK as a pozzolanic material and cement replacement help the GF to improve the toughness of RC beams.

Generally, transfer forces between concrete and rebar are provided by bonding strength as a remarkable structural property of RC beams. One of the main reasons for decreasing the load-carrying capacity of the structure is insufficient bond [44]. Chemical adhesion, friction, and mechanical interaction between the ribs of the bar and the surrounding concrete will determine the bonding strength. Based on previous researches strength is related to various factors such as concrete strength, concrete cover, and confinement of the concrete due to transverse reinforcement and bar geometry. It is expected that the bonding strength in RC beams containing fiber is more than the plain RC [8]. On the other hand and based on previous researches, since the diffusion coefficient of chloride ions in (R+G)C is less than (R+P)C [26], it seems that the permeability of (R+G)C is less than (R+P)C. Thereby, it is expected that due to less presence of aggressive ions and stronger bonding of GF rather than PF with surrounding cement matrix, the flexural capacity and toughness of (R+G)C are more than (R+P)C.

Figure 8 shows the load-deflection diagrams for RC and (R+S)C beams at 28, 90, and 180 days in the Oman Sea tidal zone.

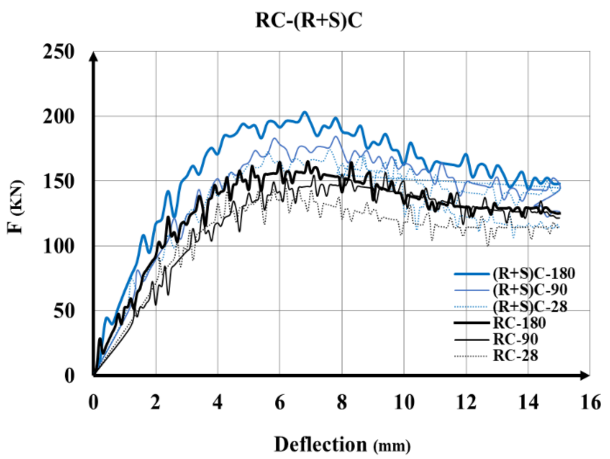


Figure 8. Load-deflection diagrams of RC and (R+S)C beams

According to Figure 8, (R+S)C has 20 to 23% higher force bearing capacity than RC beams in marine tidal zone till 180 days. On the other hand, growth in toughness by adding PF to RC beams is the same as force bearing capacity. The role of SF in transferring the tensile stress and inhibiting the crack width in concrete elements is bolder than PF and GF because of their physical properties. Generally, the role of SF in limitation of concrete cracks can be in micro and macro scales. At the micro-scale, the beginning of cracks can be stopped or its development can be prevented by SF. After the formation of macro-cracks, SF by providing effective mechanisms in bridging and reducing the rate of cracking, improve the toughness and ductility[45][46]. While the role of PF and GF because of their length and other properties in arresting the micro cracks is more than macro cracks. Consequently, the load-bearing capacity and toughness of (R+S)C beams are higher than (R+P)C and (R+G)C.

Considering the marine environment, there is a doubt that corrosion of SF can be damaged the RC beams and load-bearing capacity and toughness will be decreased or not. It seems that SF with or without corrosion can increase the force-bearing capacity and toughness of RC in marine environments. The reasons for neglecting the negative effects of SF corrosion are:

a) Tensile forces from corrosion of SF is insufficient for applying force to surrounding cement matrix due to its little diameter.

b) If the crack width higher than (2-3) mm effect of corrosion is considerable [47].

c) In concrete beams containing SF, the formation of self-healing products is great.

d) In (R+S)C beams, the SF is dispersed randomly. Therefore connecting rebar and fiber in the cover zone of (R+S)C is possible. Thereby, the extension of the anodic region from rebar to SF will be possible. Hence, until the presence of hydroxyl ions, SF will be sacrificial anodic zone and corrosion in the cathodic region is happened. Consequently, SF will be corroded before rebar corrosion and other disconnected SF to rebar will be preserved by the cement alkalinity [48].

Therefore not only existence of little corrosion on SF causes a negative effect on fiber performance but also this phenomenon leads to an increase in the cement-fiber interface friction. On the other hand, based on previous studies, concrete beams containing SF have less chloride ion permeability than PF and GF reinforced concrete. Hence the rate of rebar corrosion in (R+S)C cylinder specimens is less than (R+P)C and (R+G)C [49][50]. Therefore the friction between a rebar-cement interface in (R+S)C is higher than (R+G)C and (R+P)C. Thereby, higher load-bearing capacity and toughness of (R+S)C beams rather than (R+P)C and (R+G)C is reasonable.

3.2. Effect of hybrid (S+P)F on fracture toughness of green RC beams in Oman Sea tidal zone

Figure 9 presents the load-deflection diagrams for RC and (R+S+P)C beams at 28, 90, and 180 days in the Oman Sea tidal zone

As shown in Figure 9, (R+S+P)C has 26 to 31% higher force bearing capacity than RC beams in marine tidal zone till 180 days. On the other hand, toughness by adding PF and SF to RC beams is improved by 28 to 14% approximately.

Generally and based on previous researches, the main effect of microfibers (such as PF and GF in this paper) is an improvement of the shrinkage and early cracks rather than arresting the macro cracks.

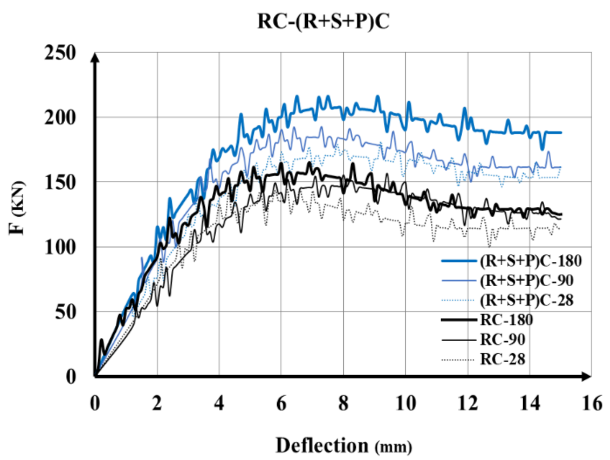


Figure 9. Load-deflection diagrams of RC and (R+S+P)C beams

In other words, it is expected that the effect of microfiber in ductility and impact resistance is less than the load-bearing capacity of concrete beams [51][52]. On the other hand, in hybrid fiber reinforced concretes (HFRC) by use of two or more different fibers achieve superior properties and better performance is possible [9].

According to previous studies, in HFRC, one type of fiber (generally microfiber) which is stronger and stiffer enhances the first crack stress and ultimate strength. Also, toughness, strain capacity, and ductility are related to the second type of fiber, which is more flexible and ductile in the post-cracking zone [51]. However, despite the benefits use of hybrid fiber in concrete elements, there is a significant problem in transition zone of HFRC [53]. In concrete containing mono fiber, there is a lot of porosity in thick transition zone which is more about HFRC [54]. Hence, reduction of porosity and consolidate this transition zone in fiber reinforced concrete, especially in HFRC will be essential and inevitable. Consequently, the use of materials that decrease the porosity in transition zone is one of the solutions. Nowadays, pozzolanic materials, which have cementitious character when composing with $Ca(OH)_2$ in water solution, is used as a Portland cement replacement in concrete for more consolidation of the cement matrix. Against this background, in this research, MK as a cement replacement can reduce the porosity in transition zones in HFRC and enhance the mechanical properties [9]. On the other hand, applying the MK will be helped to decrease cement and greenhouse gas.

Therefore, in (R+S+P)C composites, SF macro fiber by arresting the micro-cracks cause the toughness and ductility is improved. Meanwhile, shrinkage and early cracks are limited and delayed by PF micro cracks. In other words, the performance of micro and macro fiber complements each other.

3.3. Effect of hybrid (S+G)F on fracture toughness of green RC beams in Oman Sea tidal zone

Figure 10 shows the load-deflection diagrams for RC and (R+S+G)C beams at 28, 90, and 180 days in the Oman Sea tidal zone.

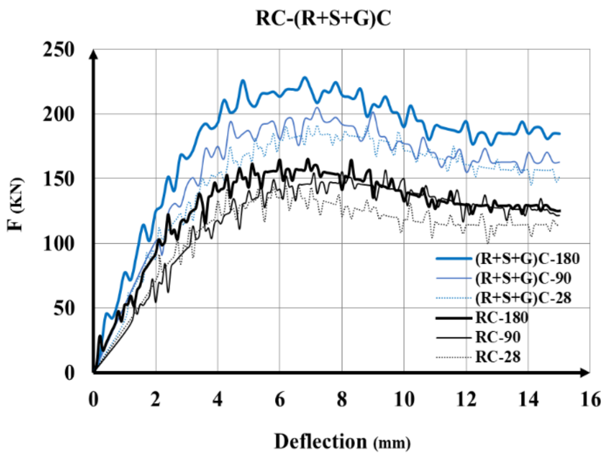


Figure 10. Load-deflection diagrams of RC and (R+S+G)C beams

According to Figure 10, (R+S+G)C has 32 to 38% higher force bearing capacity than RC beams in marine tidal zone till 180 days. Also, the toughness of RC by adding SF and GF is increased 37 to 41% approximately. Based on previous studies, the advantage of inorganic microfibers such as GF and metallic macro SF are achieving superior tensile strength, fracture toughness, and improvement of first crack strength [55]. Therefore, it is expected that (R+S+G)C will have a higher force bearing capacity and toughness rather than RC beams.

In RC beams, bonding between rebar and surrounding concrete is a significant parameter to transfer the force, strain compatibility, and composite action. By reducing the bond strength, load-bearing capacity and ductility will be decreased. Generally, bonding strength depends on chemical adhesion, friction, and mechanical interaction between the rebar and the surrounding concrete. On the other hand and according to previous studies, in RC beams with small diameter rebar, the role of fibers in bearing bond strength is not remarkable. But with increasing the rebar diameter, the confining effect of fibers with surrounding concrete and rebar will grow. Also GF has higher bonding with surrounding concrete rather than PF. Consequently, the confining effect of GF with rebar is higher than PF [8].

One of the unique properties of GF rather than PF is more uniform distribution in cement paste which leads to more cohesive behavior. Consequently, arresting the crack propagation in all directions will be more perfectly done. Thereby, the force required to pull out the fibers is increased and load-bearing capacity and toughness of (R+S)C by adding GF are grown [56]. Meanwhile, since the permeability and rebar corrosion rate of concrete containing GF against aggressive ions is lower than PF reinforced concrete, it is expected that bonding between rebar and surrounding concrete in (R+S+G)C will be higher than (R+S+P)C. Therefore, higher load-bearing capacity and toughness of (R+S+G)C rather than (R+S+P)C is justifiable.

4. Conclusion

This experimental research presented the study of load-bearing capacity and toughness of RC beams containing mono or hybrid fiber in tidal zone of the Oman Sea. Two types of mono fiber and three types of hybrid fibers were used. Mono fiber was PF, GF, and SF and hybrid ones were (S+P)F and (S+G)F. The hybrid beams were loaded until 15 mm deflection. The following conclusions till 180 days can be drawn:

1. RC beams containing PF have higher force bearing capacity and toughness (about 18 and 13%, respectively) rather than RC beams. On the other hand, GF causes an increase in force bearing capacity the same as toughness of RC beams (14% approximately). According to the little length of GF and PF and their main role in arresting the micro crack, the effect of these fibers on RC beams is about equal.

2- By the addition of SF to RC beams, flexural capacity and toughness are increased 23%. The more growth in mechanical behavior of RC rather than adding PF and GF is related to the role of SF in arresting the macro crack and more bonding strength of rebar with the surrounding concrete.

3- Effect of (S+P)F on load-carrying capacity and toughness of RC beams is higher (about 13 and 20%, respectively) than mono PF and GF. Due to the synergy role of macro SF and micro PF, this result will be justifiable.

4- RC beams containing (S+G)F compared to RC have 33 and 41% higher flexural capacity and toughness, respectively. This is because GF more bonding with surrounding cement paste rather than PF.

5. References

[1] B. V. Venkatarama Reddy and K. S. Jagadish, "Embodied energy of common and alternative building materials and technologies," Energy Build., vol. 35, no. 2, pp. 129–137, 2003, doi: 10.1016/S0378-7788(01)00141-4.

[2] J. S. Damtoft, J. Lukasik, D. Herfort, D. Sorrentino, and E. M. Gartner, "Sustainable development and climate change initiatives," Cem. Concr. Res., vol. 38, no. 2, pp. 115–127, 2008, doi: 10.1016/j.cemconres.2007.09.008.

[3] A. M. Rashad and S. R. Zeedan, "The effect of activator concentration on the residual strength of alkali-activated fly ash pastes subjected to thermal load," Constr. Build. Mater., vol. 25, no. 7, pp. 3098–3107, 2011, doi: 10.1016/j.conbuildmat.2010.12.044.

[4] S. S. Park and H. Y. Kang, "Characterization of fly ash-pastes synthesized at different activator conditions," Korean J. Chem. Eng., vol. 25, no. 1, pp. 78–83, 2008, doi: 10.1007/s11814-008-0013-6.

[5] A. M. Rashad, "Metakaolin as cementitious material: History, scours, production and composition-A comprehensive overview," Constr. Build. Mater., vol. 41, pp. 303–318, 2013, doi: 10.1016/j.conbuildmat.2012.12.001.

[6] B. Kim, A. J. Boyd, and J. Y. Lee, "Durability performance of fiber-reinforced concrete in severe environments," J. Compos. Mater., vol. 45, no. 23, pp. 2379–2389, 2011, doi: 10.1177/0021998311401089.

[7] B. Kim, A. J. Boyd, H. S. Kim, and S. H. Lee, "Steel and synthetic types of fibre reinforced concrete exposed to chemical erosion," Constr. Build. Mater., vol. 93, pp. 720–728, 2015, doi: 10.1016/j.conbuildmat.2015.06.023.

[8] N. Ganesan, P. V. Indira, and M. V. Sabeena, "Bond stress slip response of bars embedded in hybrid fibre reinforced high performance concrete," Constr. Build. Mater., vol. 50, pp. 108–115, 2014, doi: 10.1016/j.conbuildmat.2013.09.032.

[9] P. Rashiddadash, A. A. Ramezanianpour, and M. Mahdikhani, "Experimental investigation on flexural toughness of hybrid fiber reinforced concrete (HFRC) containing metakaolin and pumice," Constr. Build. Mater., vol. 51, pp. 313–320, Jan. 2014, doi: 10.1016/j.conbuildmat.2013.10.087.

[10] E. R. Silva, J. F. J. Coelho, and J. C. Bordado, "Strength improvement of mortar composites reinforced with newly hybrid-blended fibres: Influence of fibres geometry and morphology," Constr. Build. Mater., vol. 40, pp. 473–480, 2013, doi: https://doi.org/10.1016/j.conbuildmat.2012.11.017.

[11] K. T. Soe, Y. X. Zhang, and L. C. Zhang, "Material properties of a new hybrid fibre-reinforced engineered cementitious composite," Constr. Build. Mater., vol. 43, pp. 399–407, 2013, doi: https://doi.org/10.1016/j.conbuildmat.2013.02.021.

[12] D. E. Nassani, "Experimental and analytical study of the mechanical and flexural behavior of hybrid fiber concretes," Structures, vol. 28, no. September, pp. 1746–1755, 2020, doi: 10.1016/j.istruc.2020.10.014.

[13] M. Glavind and T. Aarre, "High-Strength Concrete with Increased Fracture-Toughness," MRS Proc., vol. 211, p. 39, Feb. 1990, doi: 10.1557/PROC-211-39.

[14] E. S. Larsen and H. Krenchel, "Durability of FRC-Materials," MRS Proc., vol. 211, p. 119, Feb. 1990, doi: 10.1557/PROC-211-119.

[15] A. Bentur, S. Diamondt, and S. Diamond, "Effect of ageing of glass fibre reinforced cement on the response of an advancing crack on intersecting a glass fibre strand," Int. J. Cem. Compos. Light. Concr., vol. 8, no. 4, pp. 213–222, 1986.

[16] N. Banthia and R. Gupta, "Hybrid fiber reinforced concrete (HyFRC): fiber synergy in high strength matrices," Mater. Struct., vol. 37, no. 10, pp. 707–716, 2004.

[17] H. Mihashi, S. F. U. Ahmed, and A. Kobayakawa, "Corrosion of Reinforcing Steel in Fiber Reinforced Cementitious Composites," J. Adv. Concr. Technol., vol. 9, no. 2, pp. 159–167, 2011, doi: 10.3151/jact.9.159.

[18] A. Caggiano, S. Gambarelli, E. Martinelli, N. Nisticò, and M. Pepe, "Experimental characterization of the post-cracking response in Hybrid Steel/Polypropylene Fiber-Reinforced Concrete," Constr. Build. Mater., vol. 125, pp. 1035–1043, 2016, doi: 10.1016/j.conbuildmat.2016.08.068.

[19] L. Huang, Y. Chi, L. Xu, P. Chen, and A. Zhang, "Local bond performance of rebar embedded in steel-polypropylene hybrid fiber reinforced concrete under monotonic and cyclic loading," Constr. Build. Mater., vol. 103, pp. 77–92, 2016, doi: 10.1016/j.conbuildmat.2015.11.040.

[20] L. Huang, L. Xu, Y. Chi, F. Deng, and A. Zhang, "Bond strength of deformed bar embedded in steel-polypropylene hybrid fiber reinforced concrete," Constr. Build. Mater., vol. 218, pp. 176–192, Sep. 2019, doi: 10.1016/j.conbuildmat.2019.05.096.

[21] J.-P. Won, C.-G. Park, H.-H. Kim, S.-W. Lee, and C.-I. Jang, "Effect of fibers on the bonds between FRP reinforcing bars and high-strength concrete," Compos. Part B-engineering - Compos PART B-ENG, vol. 39, pp. 747–755, Jul. 2008, doi: 10.1016/j.compositesb.2007.11.005.

[22] D.-Y. Yoo, H.-O. Shin, J.-M. Yang, and Y.-S. Yoon, "Material and bond properties of ultra high

performance fiber reinforced concrete with micro steel fibers," Compos. Part B Eng., vol. 58, pp. 122–133, 2014, doi: https://doi.org/10.1016/j.compositesb.2013.10.081.
[23] J. Li, X. Gao, and P. Zhang, "Experimental investigation on the bond of reinforcing bars in high performance concrete under cyclic loading," Mater. Struct., vol. 40, no. 10, pp. 1027–1044, 2007, doi: 10.1617/s11527-006-9201-1.
[24] S. Gali and K. V. L. Subramaniam, "Cohesive stress transfer and shear capacity enhancements in hybrid steel and macro-polypropylene fiber reinforced concrete," Theor. Appl. Fract. Mech., vol. 103, no. December 2018, p. 102250, 2019, doi: 10.1016/j.tafmec.2019.102250.
[25] I. Sadrinejad, M. M. Ranjbar, and R. Madandoust, "Influence of hybrid fibers on serviceability of RC beams under loading and steel corrosion," Constr. Build. Mater., vol. 184, pp. 502–514, 2018, doi: 10.1016/j.conbuildmat.2018.07.024.
[26] J. Liu, Y. Jia, and J. Wang, "Calculation of chloride ion diffusion in glass and polypropylene fiber-reinforced concrete," Constr. Build. Mater., vol. 215, pp. 875–885, 2019, doi: 10.1016/j.conbuildmat.2019.04.246.
[27] S. R. R. T. Prathipati, I. Khan, C. B. K. Rao, and H. Kasagani, "A study on the fiber distribution characteristics of hybrid fiber reinforced high strength concrete with steel and glass fibers," Mater. Today Proc., no. xxxx, 2020, doi: 10.1016/j.matpr.2020.07.341.
[28] C. C. Test, T. Drilled, C. Concrete, and S. T. Panels, "C 1609/C 1609M-05 Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading) 1," Astm, vol. i, no. C 1609/C 1609M-05, pp. 1–8, 2013, doi: 10.1520/C1609.
[29] P. Hughes et al., "Microscopic examination of a new mechanism for accelerated degradation of synthetic fibre reinforced marine concrete," Constr. Build. Mater., vol. 41, pp. 498–504, 2013, doi: 10.1016/j.conbuildmat.2012.12.022.
[30] M. Sappakittipakorn and N. Banthia, "Corrosion of Rebar and Role of Fiber Reinforced Concrete," J. Test. Eval., vol. 40, no. 1, pp. 127–136, Jan. 2012, doi: 10.1520/JTE103873.
[31] C. G. Berrocal, I. Löfgren, K. Lundgren, and L. Tang, "Corrosion initiation in cracked fibre reinforced concrete: Influence of crack width, fibre type and loading conditions," Corros. Sci., vol. 98, pp. 128–139, 2015, doi: https://doi.org/10.1016/j.corsci.2015.05.021.
[32] J. Blunt, G. Jen, and C. P. Ostertag, "Enhancing corrosion resistance of reinforced concrete structures with hybrid fiber reinforced concrete," Corros. Sci., vol. 92, pp. 182–191, 2015, doi: https://doi.org/10.1016/j.corsci.2014.12.003.
[33] R. H. Haddad and A. M. Ashteyate, "Role of synthetic fibers in delaying steel corrosion cracks and improving bond with concrete," Can. J. Civ. Eng., vol. 28, no. 5, pp. 787–793, Oct. 2001, doi: 10.1139/l01-037.
[34] C. G. Berrocal, I. Fernandez, K. Lundgren, and I. Löfgren, "Corrosion-induced cracking and bond behaviour of corroded reinforcement bars in SFRC," Compos. Part B Eng., vol. 113, pp. 123–137, 2017, doi: https://doi.org/10.1016/j.compositesb.2017.01.020.
[35] A. Larena and G. Pinto, "The effect of surface roughness and crystallinity on the light scattering of polyethylene tubular blown films," Polym. Eng. Sci., vol. 33, no. 12, pp. 742–747, Jun. 1993, doi: https://doi.org/10.1002/pen.760331204.
[36] N. Ranjbar and M. Zhang, "Fiber-reinforced geopolymer composites: A review," Cem. Concr. Compos., vol. 107, p. 103498, 2020, doi: 10.1016/j.cemconcomp.2019.103498.
[37] T. Simões, H. Costa, D. Dias-da-Costa, and E. Júlio, "Influence of fibres on the mechanical behaviour of fibre reinforced concrete matrixes," Constr. Build. Mater., vol. 137, pp. 548–556, 2017, doi: 10.1016/j.conbuildmat.2017.01.104.
[38] Z. Sun and Q. Xu, "Microscopic, physical and mechanical analysis of polypropylene fiber reinforced concrete," Mater. Sci. Eng. A, vol. 527, no. 1–2, pp. 198–204, 2009, doi: 10.1016/j.msea.2009.07.056.
[39] S. Marikunte, C. Aldea, and S. P. Shah, "Durability of glass fiber reinforced cement composites," Adv. Cem. Based Mater., vol. 5, no. 3–4, pp. 100–108, 1997, doi: 10.1016/S1065-7355(97)00003-5.
[40] P. J. M. Bartos and W. Zhu, "Effect of microsilica and acrylic polymer treatment on the ageing of GRC," Cem. Concr. Compos., vol. 18, no. 1, pp. 31–39, 1996, doi: https://doi.org/10.1016/0958-9465(95)00041-0.
[41] S. Marikunte, C. Aldea, and S. P. Shah, "Durability of glass fiber reinforced cement composites:: Effect of silica fume and metakaolin," Adv. Cem. Based Mater., vol. 5, no. 3, pp. 100–108, 1997, doi: https://doi.org/10.1016/S1065-7355(97)00003-5.
[42] A. Enfedaque, L. S. Paradela, and V. Sánchez-Gálvez, "An alternative methodology to predict aging effects on the mechanical properties of glass fiber reinforced cements (GRC)," Constr. Build. Mater., vol. 27, no. 1, pp. 425–431, 2012, doi: https://doi.org/10.1016/j.conbuildmat.2011.07.025.
[43] A. Enfedaque, D. Cendón, F. Gálvez, and V. Sánchez-Gálvez, "Analysis of glass fiber reinforced cement (GRC) fracture surfaces," Constr. Build. Mater. - CONSTR BUILD MATER, vol. 24, pp. 1302–1308, Jul. 2010, doi: 10.1016/j.conbuildmat.2009.12.005.
[44] S. Chao, A. Naaman, and G. Parra-Montesinos, "Bond Behavior of Reinforcing Bars in Tensile Strain-

Hardening Fiber-Reinforced Cement Composites," Aci Struct. J., vol. 106, pp. 897–906, 2009.
[45] N. Banthia and R. Gupta, "Hybrid fiber reinforced concrete (HyFRC): fiber synergy in high strength matrices," Mater. Struct., vol. 37, no. 10, pp. 707–716, 2004, doi: 10.1007/BF02480516.
[46] N. Banthia and M. Sappakittipakorn, "Toughness enhancement in steel fiber reinforced concrete through fiber hybridization," Cem. Concr. Res., vol. 37, pp. 1366–1372, Sep. 2007, doi: 10.1016/j.cemconres.2007.05.005.
[47] J.-L. Granju and S. Ullah Balouch, "Corrosion of steel fibre reinforced concrete from the cracks," Cem. Concr. Res., vol. 35, no. 3, pp. 572–577, 2005, doi: https://doi.org/10.1016/j.cemconres.2004.06.032.
[48] H. Mihashi, S. F. U. Ahmed, and A. Kobayakawa, "Corrosion of Reinforcing Steel in Fiber Reinforced Cementitious Composites," J. Adv. Concr. Technol., vol. 9, no. 2, pp. 159–167, 2011, doi: 10.3151/jact.9.159.
[49] D.-Y. Yoo, N. Banthia, J.-M. Yang, and Y.-S. Yoon, "Size effect in normal- and high-strength amorphous metallic and steel fiber reinforced concrete beams," Constr. Build. Mater., vol. 121, pp. 676–685, 2016, doi: https://doi.org/10.1016/j.conbuildmat.2016.06.040.
[50] S. Abbas, A. M. Soliman, and M. L. Nehdi, "Exploring mechanical and durability properties of ultra-high performance concrete incorporating various steel fiber lengths and dosages," Constr. Build. Mater., vol. 75, pp. 429–441, 2015, doi: https://doi.org/10.1016/j.conbuildmat.2014.11.017.
[51] A. Bentur and S. Mindess, Fibre reinforced cementitious composites. London; New York: Elsevier Applied Science, 1990.
[52] A. Bentur and S. Mindess, "Introduction," Fibre Reinf. Cem. Compos., pp. 21–30, 2020, doi: 10.1201/9781482267747-8.
[53] D. Winslow and D. Liu, "The pore structure of paste in concrete," Cem. Concr. Res., vol. 20, no. 2, pp. 227–235, 1990, doi: 10.1016/0008-8846(90)90075-9.
[54] J. F. Lamond and J. H. Pielert, Eds., No Title. West Conshohocken, PA: ASTM International, 2006.
[55] N. Banthia and M. Sappakittipakorn, "Toughness enhancement in steel fiber reinforced concrete through fiber hybridization," Cem. Concr. Res., vol. 37, no. 9, pp. 1366–1372, 2007, doi: 10.1016/j.cemconres.2007.05.005.
[56] M. Saffari Tabalvandani, H. A. Biria, and P. Kaafi Siaestalkhi, "Glass Fiber Reinforced Concrete Exclusive Assets and Applications in Construction," no. January, 2012.

Available online at: www. Ijcoe.org

Damage localization and quantification in the Catwalk of Foroozan offshore complex using improved modal strain energy method

Mehdi Alavinezhad[1], Madjid Ghodsi Hassanabad [2*], Mohammad Javad Ketabdari[3], Masoud Nekooei[4]

[1] PhD student, Department of Marine Industries, Science and Research Branch, Islamic Azad University, Tehran, Iran; alavi.mehdi@yahoo.com
[2] Assistant professor, Department of Marine Industries, Science and Research Branch, Islamic Azad University, Tehran, Iran; m.ghodsi@srbiau.ac.ir*
[3] Associate Professor, Department of Maritime Engineering, Amirkabir University of Technology, Tehran, Iran; ketabdar@aut.ac.ir
[4] Assistant professor, Department of Civil Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran; nekooei@srbiau.ac.ir

ARTICLE INFO

Article History:
Received: 18 Nov. 2020
Accepted: 09 May. 2021

Keywords:
Offshore complex
Catwalk
Damage identification
Improved modal strain energy
Stubbs index

ABSTRACT

As one of the most important components of an offshore oil and gas complex, Catwalk (access bridge) provides support for equipment and act as a passage for staff. Therefore, any damage in this structure may result in casualties as well as financial and environmental losses. Hence, identifying the location and severity of damage in these structures is of a great importance. As a common SHM method, modal strain energy uses the changes in the dynamic properties of the structure for identifying the damage location and severity. Considering natural frequencies in the process of the damage localization is one of modifications that has been successfully applied to this method. In order to show the robustness of this method for identifying damages in real class offshore structures with a large number of elements, the improved modal strain energy (IMSE) method is applied for damage localization and quantification in the access bridge of Foroozan platform in the Persian Gulf. The results showed that the IMSE damage index is more accurate than the original Stubbs index. Both the single and multiple damages were predicted with a good accuracy with this method. However, the method was more accurate in locating the damages in horizontal elements as well as the elements far from the supports of the structure.

1. Introduction

In shallow waters such as the Persian Gulf, steel jacket platforms are commonly used for oil and gas extraction. During their service life, offshore structures are exposed to different loads such as the loads during construction, transportation and installation as well as the loads during operation such as drilling and extraction, environmental loads such as wind, wave, ice and current loads, and accidental loads such as earthquake, fire, storms and ship collisions. Consequently, some damages such as fatigue and crack in joints, corrosion of the elements, perforation and flooding of members, and even total failure and sudden destruction of the platform may occur. Various types of offshore steel structures are found in offshore oil and gas production complexes, including drilling/well-protector platforms, tender platforms, self-contained platforms (template and tower), production platforms, quarter platforms, flare jacket and flare tower platforms, auxiliary platforms, bridges and heliports [1]. Each of these types of platforms has its own characteristics from an operational point of view. One of the most important components of offshore oil and gas complexes is the access bridge between different platforms. Due to the corrosive environment of the installation site as well as the possibility of various damages to the structural members that cause huge financial and human losses, structural health monitoring of these structures is very important.

Various methods have been used for structural health monitoring of structures including access bridges in offshore installations. One of these methods is the visual inspection that gives important information about the condition of the structure. Despite some advantages, this method requires a lot of time and money. Also, due to the unavailability of some members, visual inspection can not detect the damage in some unavailable members. In addition, detecting internal damages and their origin is not possible by this method. In order to increase the safety and ensure the safety of the structure, in recent years, much attention has been paid to non-destructive damage detection methods. One of these methods is using vibrational properties of the structure to assess the damage at the structure level, which is used as a complementary solution along with visual inspections [2,3]. In vibration-based damage detection methods, the modal properties of the structure (natural frequencies, mode shapes and modal damping) are a function of its physical properties. Therefore, by using changes in the static or dynamic response of structures, changes in their physical properties and consequently structural damage can be identified in the early stages. This resulted in a reduction in maintenance costs and prevention of structural failure.

As its purpose is monitoring the structural and operational conditions to prevent catastrophic failures and providing the necessary quantitative design data for engineers and owners of the structure, structural health monitoring has so far attracted a great deal of attention from researchers around the world. As one of the first attempts to detect damages in structures, Cawley and Adams (1979) used the natural frequencies of the structure as an indicator to detect the location of the damage [4]. Examining the effects of diagonal bracing on the frequency and mode shapes of the platform deck, Shahrivar and Bouwkamp (1986) used vibrational information to detect damages in an offshore steel platform [5]. Frequency and mode shapes of the structure were successfully used for damage localization and quantification by Hansen and Vanderplaats (1990) for damage detection in the structure [6]. Doebling et al. (1993) proposed a method based on modal strain energy for selecting a set of vibrational modes of structures and detecting structural damage in them [7]. Presenting an algorithm for damage localization and quantification in jacket platforms, Kim and Stubbs (1995) determined the location of the damage and estimated its severity considering the changes in the mode shapes and then formulated a method to determine the modal parameters of the structure [8]. Kim and Stubbs (1995 & 1996) proposed a damage index based on modal strain energy method for beam-like structures, examined the efficiency of this method on a steel bridge, and correctly detected the location of the damage [9,10]. Salawu (1997) conducted a study on the use of natural frequencies for damage detection and concluded that the use of natural frequencies alone was not sufficient for detection of local damage, although it could be effective in general damage detection [11]. Examining five damage detection methods, including modal strain energy damage index (MSE-DI) method, mode shape curvature method, change in uniform load surface curvature method, and change in stiffness method on a steel bridge, Farrar and Jauregui (1998) concluded that modal strain energy damage index method had higher accuracy compared to other methods [12]. Developing an improved, more accurate damage index, Kim and Stubbs (2002), tested the performance of their index on a two-span beam [13]. Li, et al., (2002) proposed a method for damage localization in a planar element using the mode shapes obtained by the Rayleigh–Ritz method, and by numerical modeling, demonstrated that this method has a high ability to detect single and multiple damages [14]. Using modal strain energy changes via two indicators of compression modal strain energy change ratio (CMSECR) and flexural modal strain energy change ratio (FMSECR), Yang et al. (2003) assessed damage in marine structures [15]. Ge and Lui (2005) proposed a finite element model that used the dynamic properties of the structure including modal frequencies and mode shapes for damage localization and quantification [16]. Applying the modal strain energy method for detecting damage in beams and plates, Shih et al. (2009) concluded that this method can be used to detect damage in girder and bridge decks [17]. Hu and Wu (2009) developed a modal strain energy-based damage index to detect damage in plates [18]. Seyedpoor (2012) proposed a two-step method for accurately detecting the location and severity of multiple damages in structural systems [19]. Using modal energy strain difference of the structure in intact and damaged modes to detect the location of wind turbine damage, Liu et al. (2014) provided a model based on modal strain energy method that was more sensitive than other traditional strain energy methods [20]. Considering a 31 element planar truss, a three span frame and a space truss, Seyedpoor and Yazdanpanah (2014) presented a method for identifying the location of damage based on the strain energy caused by static loads on the structure, in two intact and damaged modes and concluded that by applying a load on one node of the studied trusses and calculating the displacement of the nodes, identifying the location of the damage was easy [21]. Wang et al. (2014) used the modal strain energy method for damage localization in an offshore platform and concluded that among all the damage detection methods so far, modal strain energy-based methods are more effective than other methods in determining the location of the damage [22].

In the field of damage detection studies on bridges, Giles, et al., (2011) used the damage locating vector method (DLV) for damage localization at the second span of the Government Bridge in Rock Island, USA [23]. Modares and Waksmanski (2013) reviewing some areas of structural health monitoring, studied the new and traditional sensors used for monitoring of structural parameters such as corrosion, cracking, displacement, fatigue, force, settlement, strain, temperature, tilt, vibration, water level and wind in steel bridges [24]. Budipriyanto and Susanto (2015) used the responses obtained from a railway steel truss bridge in intact and damaged conditions when it was under the train traffic for damage localization and quantification [25]. Li and Hao, (2016) reviewed recent developments in the field of structural health monitoring, including signal processing methods for operational modal analysis, a user friendly graphical modal analysis toolkit, non-modal methods for evaluating shear joints in composite bridges and determining the free span and support conditions of pipelines, vibration based damage detection methods and model updating including the effects of uncertainty and noise as well as identifying structures under moving loads[26]. Ding, et al., (2019) practically monitored the condition of the scaffold separation process from a large steel span bridge during the bridge construction process and examined changes in strain distribution. They also modeled the bridge to simulate scaffold removal conditions using the finite element method and compared the strain distribution in the girder with the measured values [27].

This comprehensive literature study shows the high accuracy and ability of the modal strain energy method for damage detection in marine structures. The importance and high investment made in Iran's offshore oil and gas facilities, shows the need to check the health of these structures more than before. The Forouzan oil field, located between Iran and Saudi Arabia, is of great importance to the Iranian economy, and it is essential to identify any damage to the platform structure in the early stages. Due to the long service life of the country's offshore platforms and the existence of possible damage in these platforms, in this paper a comparison between the accuracy of different damage detection methods, including the Stubbs index method and improved strain energy method in order to use this method to identify real damage in Offshore platforms took place. For this purpose, the access bridge between the FY and FY-B platforms (Figure1) of Forouzan oil complex located in the Persian Gulf was studied. One of the differences between the present study and other studies is the selection of structures with a large number of members. Also, the accuracy of the method in identifying the location and severity of small and multiple injuries is one of the features of this article.

1.1. Offshore platform access bridge

A bridge with the length of 30-49 m (100-160 ft) that connects two adjacent offshore structures is called a catwalk. This bridge supports pipelines, pedestrian movement, or a bridge of materials handling [1]. The different geometries of bridges are shown in Figure 2.

Figure 1: Foroozan oil complex [28]

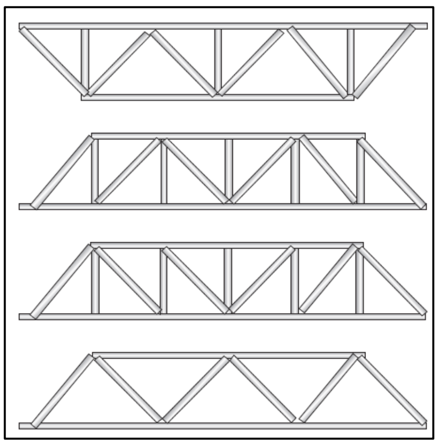


Figure 2: Different Geometries of catwalk [1]

2. Materials and Methods

2.1. Modal Strain Energy

Applying a force to an elastic body leads to a tension as well as a deformation in the body. As a consequence of this deformation, the position of the various points of the elastic object changes. Changing the point of effect of the applied load causes some work to be performed. This work, which is accompanied by the deformation of the object in the tension state, stores some energy in the form of elastic energy in the object called strain energy. Modal strain energy is a condition in which no force is applied to the structure and the structure is in free vibration state. In this condition, the modal strain energy of each element can be obtained by dynamic analysis and solving the related equations. Structural damage usually reduces the stiffness of the structure, but does not affect its mass matrix.

In a linear structure, with NE elements and N nodes, the i-th modal stiffness of structure is obtained from the following equations [13]:

$$K_i = \Phi_i^T C \Phi_i \quad (1)$$

$$K_i^* = \Phi_i^{*T} C^* \Phi_i^* \quad (2)$$

where K_i and K_i^* are the stiffness at the i-th mode, C and C^* are the stiffness matrices of the structure and Φ_i and Φ_i^* are i-th mode shaper vectors of the structure in intact and damage states, respectively. In other word, in these equations * shows the damaged state. The Stubbs damage index is obtained from the following equation [13]:

$$\beta_{ij} = \frac{E_j}{E_j^*} = \frac{[\phi_i^{*T} C_{jo} \phi_i^*] K_i}{[\phi_i^T C_{jo} \phi_i] K_i^*} \quad (3)$$

where, β_{ij} is the damage detection index for j-th element and i-th mode, E_j and E_j^* are the modulus of elasticity of the j-th element in intact and damaged conditions, respectively and C_{jo} is related to the geometric properties of the stiffness matrix. If $K_i^* \approx \phi_i^{*T} C \phi_i^*$ is set, all quantities on the right-hand side (including ϕ_i and ϕ_i^*) can be determined, or estimated from the modal parameters obtained from experimental measurements and geometry of the structure (C_{jo}). According to the above equation, the damage in j-th element and i-th mode shape is determined if $\beta_{jj} > 1$. However, if j-th element is in or near the i-th mode shape, the denominator of the above equation will tend to zero and a false prediction of the damage will be resulted. Based on the study of Kim and Stubbs [13], by considering some approximations, this limitation is overcome and the following relation is obtained:

$$\beta_j = \frac{\sum_{i=1}^{NM} (\Phi_i^{*T} C_{jo} \Phi_i^* + \sum_{i=1}^{NE} \Phi_i^{*T} C_{ko} \Phi_i^*) K_i}{\sum_{i=1}^{NM} (\Phi_i^T C_{jo} \Phi_i + \sum_{i=1}^{NE} \Phi_i^T C_{ko} \Phi_i) K_i^*} \quad (4)$$

It should be noted that since the structure stiffness matrix is not determined in the damaged mode, the stiffness matrix of the intact structure is used for both intact and damaged cases. After obtaining β_j for each element, the damage index is normalized using the following equation [13]:

$$Z_j = \frac{\beta_j - \bar{\beta}}{\sigma_\beta} \quad (5)$$

2.2. Improved modal strain energy method

In order to determine the Stubbs's index, only the mode shapes are used and natural frequencies are not considered in determining the location of the damage. However, previous researches have shown that modal frequencies can be determined much more accurately than mode shapes. Measuring the shape of the mode is more difficult than measuring normal frequencies. Mode shape is a unique feature of any structure and in practice it is not possible to measure modes for all degrees of freedom. Another problem of using modes is how to make experimental and analytical mode forms dependent.

In order to improve the Stubbs's method, Li et al. (2016) used frequency information in determining the damage index [29]. They showed that the reduction in stiffness due to damage to the structure affects the natural frequency and this can be the basis of the frequency-based damage detection method. An important advantage of this method is the ease and simplicity of determining natural frequencies. In fact, by placing a sensor in the structure, its various frequencies can be measured. It should be noted that natural frequencies are sensitive to all types of local and general damage. Eigen analysis for intact and damaged structures can be written as follows:

$$K\phi_i = \omega_i^2 M\phi_i \tag{6}$$

$$K^*\phi_i^* = \omega_i^2 M^*\phi_i^* \tag{7}$$

where M and M^* are mass matrices of the system and ω_i and ω_i^* are the i-th modal frequencies in intact and damaged modes, respectively. The improved damage index is obtained from the following equation:

$$\beta_j = \frac{\sum_{i=1}^{m}\left(\phi_i^{*T} K_j \phi_i^* + \omega_i^{*2}\phi_i^{*T} M\phi_i^*\right)\omega_i^2\phi_i^T M\phi_i}{\sum_{i=1}^{m}\left(\phi_i^T K_j\phi_i + \omega_i^2\phi_i^T M\phi_i\right)\omega_i^{*2}\phi_i^{*T} M\phi_i^*} \tag{8}$$

Using equation 5, the above index can be normalized.

2.3. Estimating the severity of the damage

If we show the ratio of the changes in the stiffness of the j-th element with α_j, so that $\alpha_j \geq -1$, we have:

$$E_j^* = E_j\left(1+\alpha_j\right) \tag{9}$$

Then, the severity of damage can be obtained from the following equation:

$$\alpha_j = \frac{\left[\phi_i^T C_{jo}\phi_i\right]}{\left[\phi_i^{*T} C_{jo}\phi_i^*\right]}\frac{K_i^*}{K_i} \tag{10}$$

2.4. Study Area

Foroozan oil field is located in the Persian Gulf, about 100 km southwest of Kharg Island export terminal. This field is located on the water border of Iran-Saudi Arabia and the Saudi Arabian part is called Marjan field. The field, owned by the National Iranian Oil Company (NIOC), was discovered in 1966 and has 2.3 billion barrels of recoverable reserves. This offshore oil field started to operate with an initial production of 100,000 barrels per day in 1987, but its production fell to 40,000 barrels per day in 2000. In order to double the crude output of the field to 80,000 barrels per day and also increase the gas production capacity, the Iranian Offshore Oil Company (IOOC) has undertaken some reconstruction and redevelopment activities, including the installation of a number of new offshore platforms. Oil and gas produced in Foroozan field are processed in two offshore production complexes FX and FZ.

2.5. Details of Foroozan oil field development

Foroozan oil field was initially developed with 66 wells, two production platforms, one production unit, 12 wellhead platforms, three separators, a desalination unit and two residential platforms named FX and FY. The two-story FX residential platform accommodates 21 people and also supports a control room, a restaurant and a theater, while FY residential platform is a three-story platform for 42 people. The hydrocarbons produced in this field are separated into crude oil, associated gases and water. Crude oil is transported through a 100-kilometer pipeline with a diameter of 20 inches to Kharg export terminal. In 2015, Foroozan oil field was renovated with 24 new production wells with two offshore platforms, including FZ-A processing unit and FY-A residential platform [30].

3. Results and discussions

3.1. Identification of damage location and severity in Catwalk of Foroozan offshore complex

In this section, damage is identified in the access bridge of Foroozan offshore complex. This access bridge is designed to connect FY-B and FY platforms. With an approximate length of 45.65 m, this bridge has a triangular shape. The section of the lower chord is of 355.60D x 15.9 WT in EL +16.75 (TBC) and the upper chord cross section is 457oD X 15.9 WT in EL.+21.250 (TBC). Steel type is API 5L x 52. A summary of the overall layout of the bridge is given in Table 1.

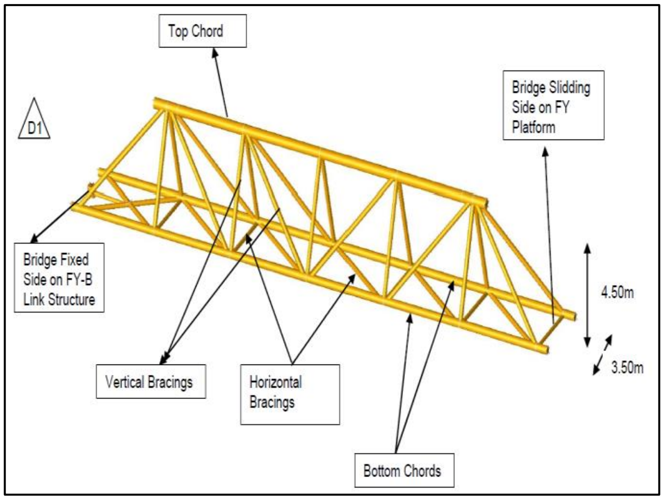


Figure 3: General view of Catwalk structure

Table 1: Specifications of the access bridge

Properties	Design data
Cross section	Triangular
Width of the bridge	3.5 m
Height of the bridge	4.5 m
Number of chords	3
Diameter and thickness of chords	457 mm and 15.9 mm
Diameter and thickness of horizontal bracings	168.3 mm and 9.5 mm
Diameter and thickness of inclined horizontal bracings	219.1 mm and 9.5 mm
Diameter and thickness of inclined vertical bracings	219.1 mm and 9.5 mm
Diameter and thickness of inclined vertical bracings	219.1 mm and 15.9 mm

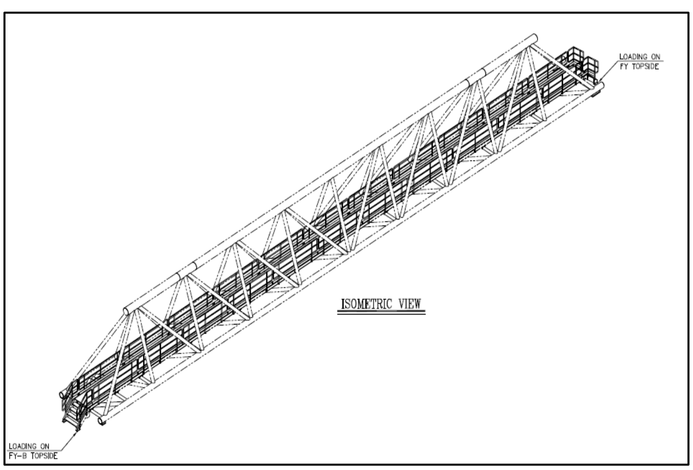


Figure 4: Isometric view of the access bridge

3.2. Applying assumed damage to the structure and defining different damage scenarios

In this research, hypothetical damage is applied by reducing the modulus of elasticity of the element in the Finite Element code. In order to show the accuracy of the modal strain energy method in identifying the location and severity of damage, different single and multiple damage scenarios have been defined. To identify damage by modal strain energy method, structural modal information in the pre- and post-damage condition is required. For this purpose, after modeling the bridge and defining the elemental stiffness and mass matrices and assembling them to achieve the global stiffness and mass matrices of the structure, eigenvectors and eigenvalues that are the mode shapes and natural frequencies of the structure, respectively, are extracted. The natural frequencies are then arranged in ascending order, with the smallest frequency being the first natural frequency of the structure and the corresponding mode shape being the first mode shape of the structure. Table 2 shows the different damage scenarios along with the first three natural frequencies of the damaged structure in each mode. The geometric location of the damaged elements is shown in Figure 5. It should be noted that a first few mode shapes of the structure are considered in the calculations related to damage identification.

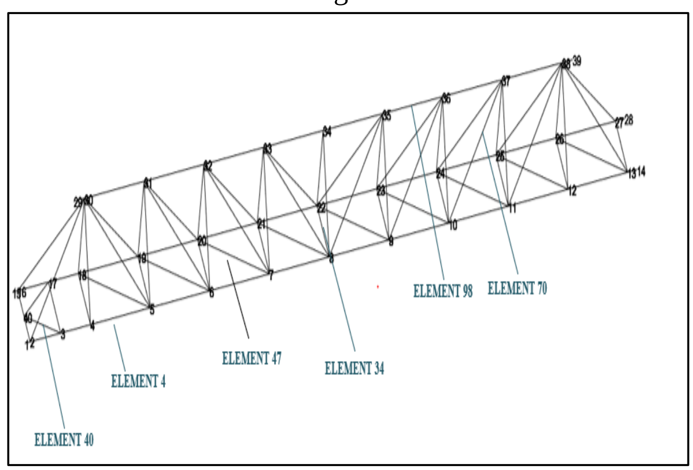


Figure 5: Created Finite Element model of the Catwalk and the hypothetical damaged elements

Table 2: Different damage scenarios to Catwalk structure and the first three natural frequencies of the structure in each scenario

Damage Scenarios	Damage Element	Damage Severity (%)	Natural Frequency (Hz)		
			First mode	Second mode	Third mode
1	4	15	5.1368	5.4146	8.6879

2	34	20	5.1377	5.4284	8.6898
3	40	10	51378	5.4276	8.6864
4	47	20	5.1377	5.4259	8.6869
5	70	10	5.1362	5.4273	8.6776
6	4 and 47	15 and 20	5.1367	5.4118	8.6849

3.3. Identifying the location and severity of damage in different scenarios

3.3.1. First scenario

In this case, a hypothetical 15% damage is applied to element No.4 which is located in the bridge chord. Mode shapes of the structure are extracted in both intact and damaged modes and using modal strain energy, the damage location and severity are plotted in Figures 6 and 7, respectively. As Figure 6 shows, the modal strain energy method determined the location of damage in the bridge chord element with high accuracy. However, it is clear that the improved modal strain energy results were slightly better than Stubbs index, such that the improved index is slightly higher in damaged elements and lower in intact elements. Figure 7 shows that the modal strain energy method accurately predicts the severity of damage to bridge chord element.

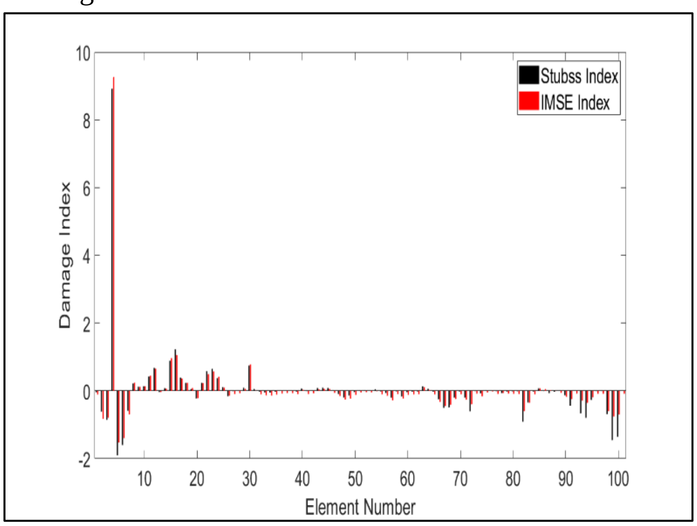


Figure 6: Damage localization results using Stubbs and IMSE indices in the first damage scenario

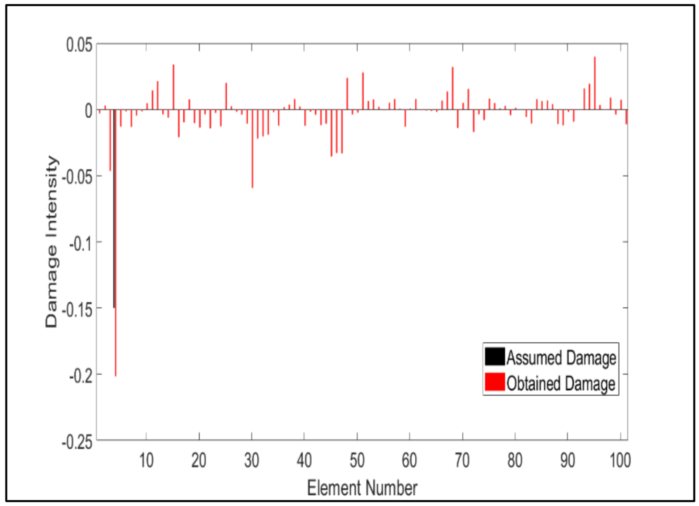


Figure 7: Damage severity estimation using modal strain energy method in the first scenario

3.3.2. second scenario

In this case, a hypothetical 20% damage is applied to element No.34 which connects the two bottom chords of the bridge. Figure 8 shows the damage localization and Figure 9 shows the damage quantification in this case. As Figure 8 shows, the improved method gives more accurate results for damage index. Figure 9 shows that the damage severity is predicted with an acceptable accuracy.

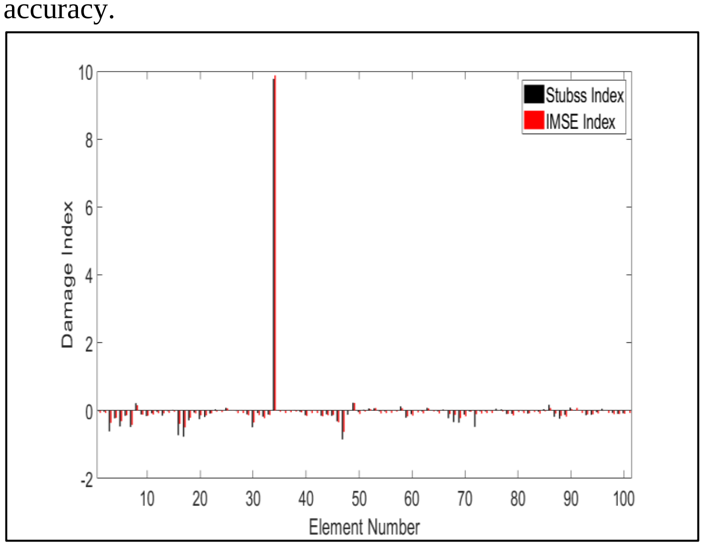


Figure 8: Damage localization results using Stubbs and IMSE indices in the second damage scenario

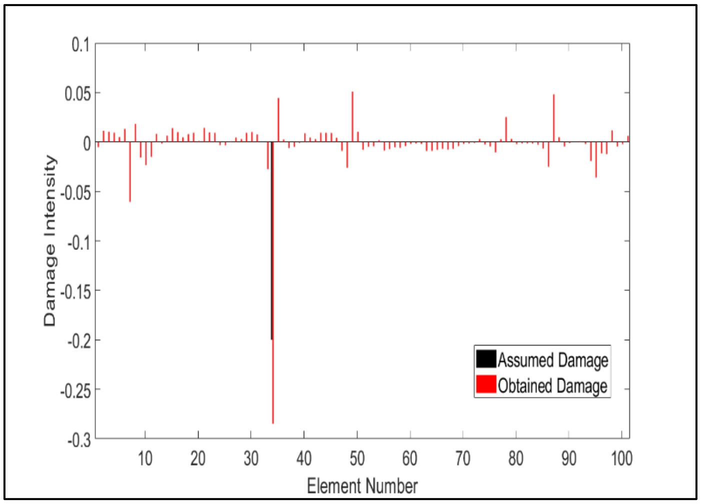


Figure 9: Damage severity estimation using modal strain energy method in the second scenario

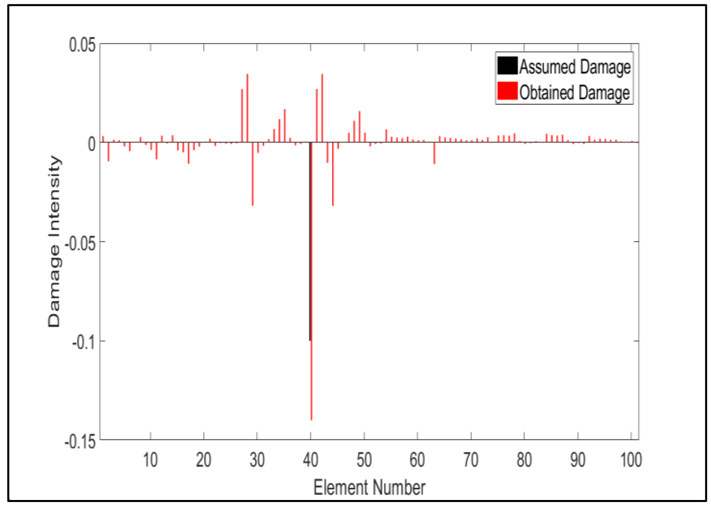


Figure 11: Damage severity estimation using modal strain energy method in the third scenario

3.3.3. Third scenario

In this case, a hypothetical 10 % damage is applied to the element No. 40 which is one of the diagonal members of the access bridge. The predicted location of the damage in this case is drawn in Figure 10, showing that the accuracy of the damage localization is improved using the IMSE index. Figure 11 also shows that the modal strain energy method accurately predicts the severity of damage for diagonal member of the access bridge.

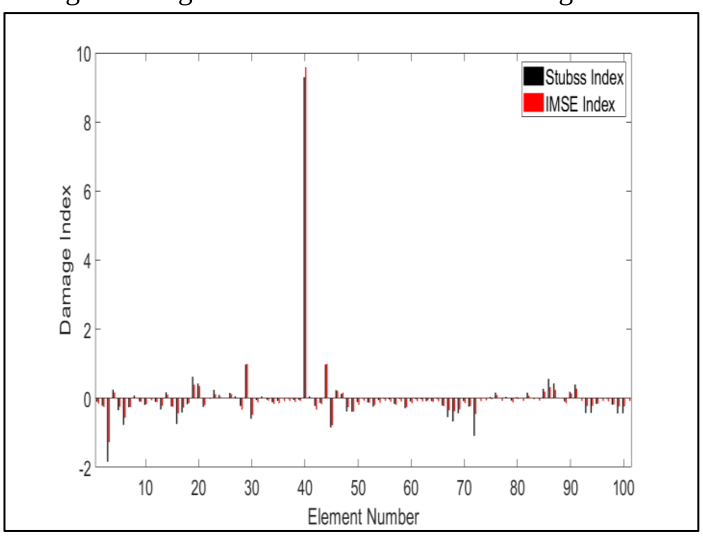


Figure 10: Damage localization results using Stubbs and IMSE indices in the third damage scenario

3.3.4. Fourth scenario

In this case, a hypothetical 20% damage is applied to element No. 47 which is one of the inclined members of the access bridge. Figure 12 shows a slight improvement in damage localization using the improved method. Figure 13 shows that the modal strain energy method was able to accurately predict the severity of damage occurred in inclined members of the access bridge.

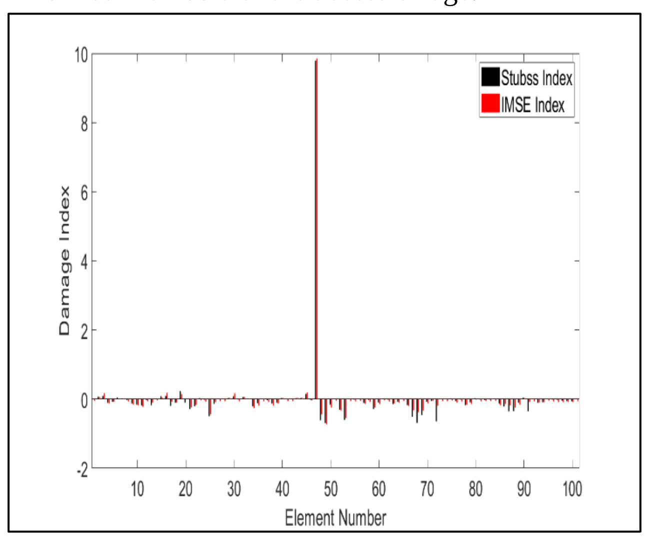


Figure 12: Damage localization results using Stubbs and IMSE indices in the fourth damage scenario

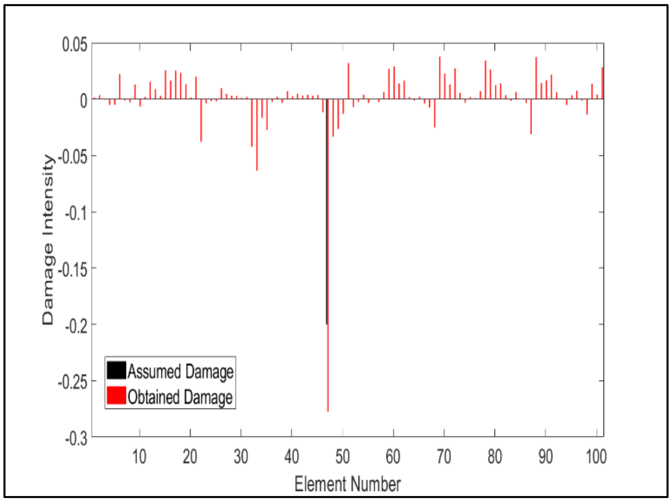


Figure 13: Damage severity estimation using modal strain energy method in the fourth scenario

3.3.5. Fifth scenario

In this case, it is assumed that member 70, as one of the inclined members connecting the lower chord to the upper chord, is damaged by 10%. Figure 14 shows a slight improvement of damage localization using the improved method. Figure 15 shows that the modal strain energy method was able to predict the severity of damage to the inclined member connecting the two chords, although the prediction accuracy was slightly reduced in comparison with the horizontal damaged element.

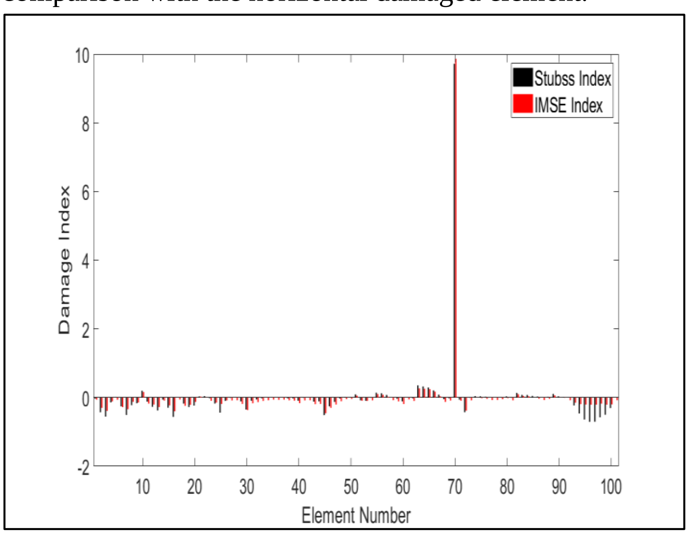


Figure 14: Damage localization results using Stubbs and IMSE indices in the fifth damage scenario

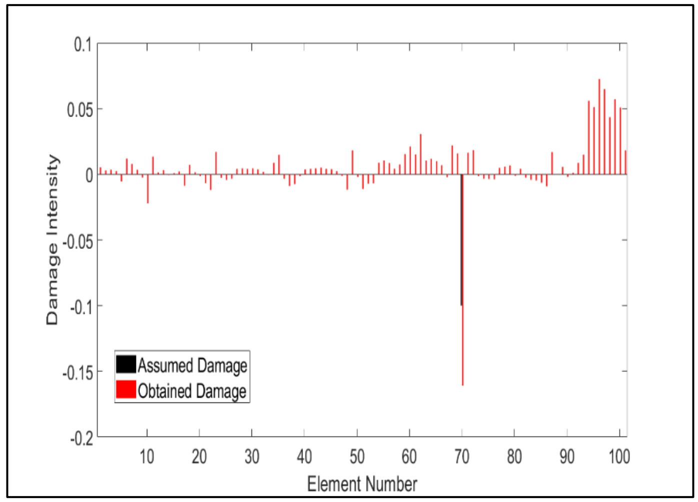


Figure 15: Damage severity estimation using modal strain energy method in the fifth scenario

3.3.6. Sixth Scenario

In this case, elements 4 and 47 (horizontal member and bracing member of the access bridge) are damaged by 15% and 20%, respectively. The results of the damage index in Figure 16 show that the modal strain energy method is able to predict the location of multiple damages with appropriate accuracy and again using the improved modal strain energy method has led to improved damage localization results. Figure 17 shows that the modal strain energy method has high accuracy in determining the severity of multiple damages.

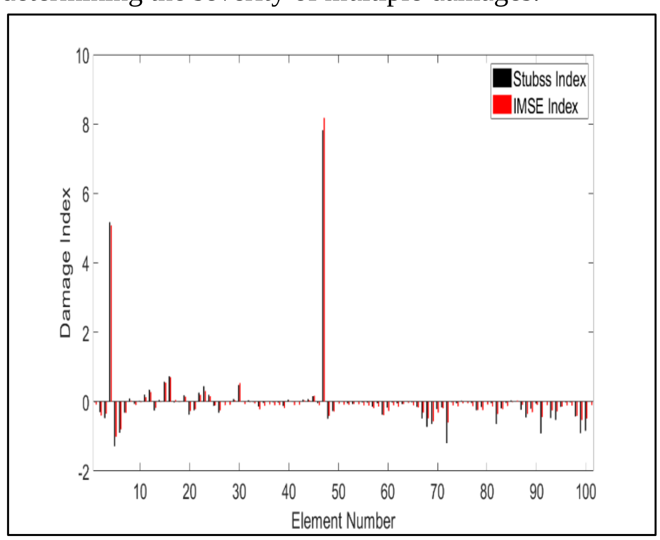


Figure 16: Damage localization results using Stubbs and IMSE indices in the sixth damage scenario

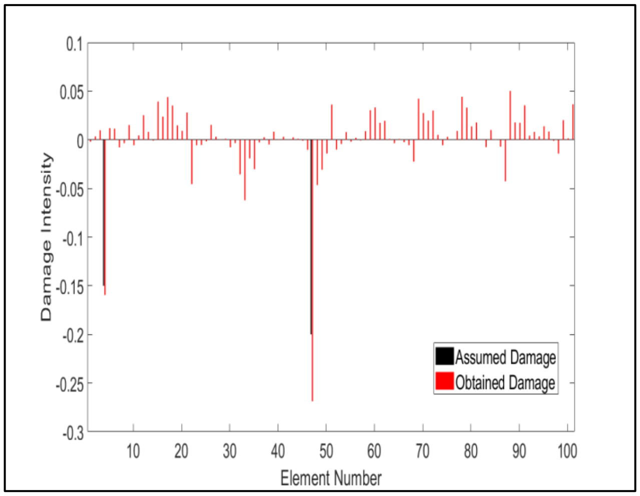


Figure 17: Damage severity estimation using modal strain energy method in the sixth scenario

4. Conclusion

As the service life of offshore structures expires, their structural health monitoring becomes important. Being a passage for staff and pipelines, access bridge that connects different offshore platforms is an important part of an offshore complex. However, it has received less attention in previous studies. In this research, using the modal strain energy method which is one of most appropriate non-destructive damage detection methods, single and multiple damages were identified at the access bridge of the Foroozan oil field in the Persian Gulf and the results of the two well-known modal strain energy-based damage indices, namely Stubbs and IMSE indices were compared. The hypothetical damage was applied to the elements that their damage was thought to have more negative effect on the structural integrity. For this purpose, the floor elements, the horizontal members of chords, the members connecting the two lower chords along with the elements connecting the lower chord to the top chord were selected as damaged elements. The results indicate the appropriate ability of the improved modal strain energy method to identify the severity and location of damage in the access bridge of offshore platforms. The method was also able to present acceptable performance in identifying both single and multiple damages. However, the accuracy of the method was higher in horizontal members than in the brace members. Also, the accuracy of damage detection in horizontal level was superior to its accuracy in inclined elements that connect lower and top chords. Also, the accuracy of damage identification increases by moving away from the supports. Finally, due to the fact that the improved modal strain energy method identifies the location of damage in structure with higher accuracy, the use of this method is recommended instead of the Stubbs index method.

Acknowledgement

The authors would like to thank the Iranian Offshore Oil Company (IOOC) for providing the drawings of the access bridge of Foroozan Oil complex.

References

[1] El-Reedy, M. A, (2015), *Introduction to offshore structures, Marine Structural Design Calculations*, s.l. : Butterworth-Heinemann, pp. 1-12.

[2] Doebling, S., et al., et al, (1996), *Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: A literature review*, s.l. : Los Alamos National Laboratory.

[3]. Balageas, D, (2006), *Introduction to Structural Health Monitoring*, Structural Health Monitoring, s.l. : Wiley, pp. 13-43.

[4]. Cawley, P. and Adams, R. D, (1979), *The location of defects in structures from measurement of natural frequencies*, The Journal of Strain Analysis for Engineering Design, Vol. 14, pp. 49-57.

[5]. Shahrivar, F. and Bouwkamp, G, (1986), *Damage detection in offshore platforms using vibration information*, Journal of Energy Resources Technology, Vol. 108, pp. 97-106.

[6]. Hansen, S. R. and Vanderplaats, G. N., (1990), *Approximation method for configuration optimization of trusses*, AIAAJ, Vol. 28, pp. 161-168.

[7]. Doebling, S., et al., et al, (1993), *Selection of experimental modal data sets for damage detection via model update*, 34th Structures, Structural Dynamics and Materials Conference.

[8]. Kim, J. T. and Stubbs, N, (1995), *Damage detection in offshore jacket structures from limited modal information*, International Journal of Offshore and Polar Engineering, Vol. 5, pp. 58-66.

[9]. Stubbs, N., Kim, J. T. and Farrar, C. R., (1995), *Field verification of a non-destructive damage localization and severity estimation algorithm*, Proceedings of the 13th International Modal Analysis Conference.

[10]. Stubbs, N. and Kim, J. T., (1996), *Damage localization in structures without baseline modal parameters*, AIAA Journal, Vol. 34, pp. 1644-1649.

[11]. Salawu, O. S., (1997), Detection of structural damage through changes in frequency: a review, Engineering Structures, Vol. 19, pp. 718-723.

[12]. Farrar, C. R. and Jauregui, D. A., (1998), *Comparative study of damage identification algorithms applied to a brdige: II. Numerical study*, Smart Materials and Structures, Vol. 7, pp. 720-731.

[13]. Kim, J. T. and Stubbs, N., (2002), *Improved damage identification method based on modal information*, Journal of Sound and Vibration, Vol. 252, pp. 223-238.

[14]. Li, Y. Y., et al., et al., (2002), *Identification of damage locations for plate-like structures using damage sensitive indices: strain modal approach*, Computers & Structures, Vol. 80, pp. 1881-1894.

[15]. Yang, H. Z., Li, H. J. and Wang, S. Q., (2003), *Damage localization of offshore platforms under ambient excitation*, China Ocean Engineering, Vol. 17, pp. 495-504.

[16]. Ge, M. and Lui, E. M, (2005), *Structural damage identification using system dynamic properties*, Computers & Structures, Vol. 83, pp. 2185-2196.

[17]. Shih, H. W., Thambiratnam, D. P. and Chan, T. H.T., (2009), *Vibration based structural damage detection in flexural members using multi-criteria approach*, Journal of Sound and Vibration, Vol. 323, pp. 645-661.

[18]. Hu, H. and Wu, C., (2009), *Development of scanning damage index for the damage detection of plate structures using modal strain energy method*, Mechanical Systems and Signal Processing, Vol. 23, pp. 274-287.

[19]. Seyedpoor, S. M., (2012), *A two stage method for structural damage detection using a modal strain energy based index and particle swarm optimization*, International Journal of Non-Linear Mechanics, Vol. 47, pp. 1-8.

[20]. Liu, F., et al., et al., (2014), *Experimental study of improved modal strain energy method for damage localisation in jecket-type offshore wind turbines*, Renewable Energy, Vol. 72, pp. 174-181.

[21]. Seyedpoor, S. M. and Yazdanpanah, O., (2014), *An efficient indicator for structural damage localization using the change of strain energy based on static noisy data*, Applied Mathematical Modeling, Vol. 38, pp. 2661-2672.

[22]. Wang, S., Liu, F. and Zhang, M., (2014), *Modal strain energy based structural damage localization for offshore platform using simulated and measured data*, Journal of Ocean University of China, Vol. 13, pp. 397-406.

[23]. Giles, R. K., et al., et al., (2011), *Structural Health Indices for Steel Truss Bridges*, Civil Engineering Topics, Vol. 4, pp. 391-399.

[24]. Modares, M. and Waksmanski, N., (2013), *Overview of structural health monitoring for steel bridges*, Practice Periodical on Structural Design and Construction, Vol. 18, pp. 187-191.

[25]. Budipriyanto, A. and Susanto, T., (2015), *Dynamic response of a steel railway bridge for the structure's condition assessment*, Procedia Engineering, Vol. 125, pp. 905-910.

[26]. Li, J. and Hao, H., (2016), *A review of recent research advances on structural health monitoring in Western Australia*, Structural Monitoring and Maintenance, Vol. 3, pp. 33-49.

[27]. Ding, Y., et al., et al., (2019), *Structural health monitoring of the scaffolding dismantling process of a long-span steel box girder viaduct based on BOTDA technology*, Advances in Civil Engineering, Vol. 2019, pp. 1-8.

[28]. [Online] http://www.iooc.co.ir/.

[29]. Li,Y., et al., et al., (2016), *An improved modal strain energy method for damage detection in offshore platform structures*, Journal of Marine Science and Application, Vol. 15, pp. 182-192.

[30]. [Online] https://www.nsenergybusiness.com/projects/forouzan-oil-field-expansion/.

Available online at www. Ijcoe.org

Rationality for Engineers: Part I- Setting the scene

Sirous F. Yasseri

Brunel University London; Sirous.Yasseri@Brunel.ac.uk.

ARTICLE INFO

Article History:
Received: 25 Feb. 2021
Accepted: 04 Jun. 2021

Keywords:
Decision making;
Heuristics;
Engineering judgment;
Intuition;
Rationality;
Rules-of-thumb;
Shortcuts;
Reasoning.

ABSTRACT

The truly complex element of modern times is not the technology, but the engineers who develop, design, manufacture, and maintain it. An engineer's job is to change/improve existing situations into more desirable ones, as well as to respond to the demands or needs of society. Engineers cannot wait until all phenomena and their implications are well understood. Engineers have worked for centuries solving problems with limited information and knowledge and are presumed to be rational decision-makers. Then, how do engineers make their decisions with limited knowledge, time, and cognitive capacity in a variety of domains? Engineers require understanding what part of information can be ignored, and what situations require fast, and timely response, resulting hopefully in a better decision by freeing cognitive capacity to make it. A rational decision-maker should choose an option that maximizes the expected benefits (utilities), although there may be significant hurdles in achieving such goals, especially in emergencies where time pressure is acute. To overcome these hurdles, most engineers revert to "rules-of-thumb", also known as heuristics. Heuristics are experience-based methods of gut feelings that can be used as an aid to solve specific problems in a particular environment. Heuristics, however, are imperfect; thus, engineers must understand their limitations. Their applicability is also limited by the context under which they were derived as well as their fit with the environment of the problem at hand. The overall objective of these four-part papers is to discuss heuristics and how they can make decision-making easier and faster for engineers. These papers also remind them of their own cognitive biases and describe ways of avoiding them. This first part aims to set the scene by providing background information. These papers address the type of rationality that engineers need to be effective build on the existing literature and liberally draws from them. Engineers cannot march on the spot while thinking for a solution, they must think while moving forward, thus there is a danger not starting on the right foot.

1. Introduction

Engineering is an overarching profession that encompasses engineers working in various fields, such as aerospace, interplanetary exploration, offshore, chemical processing, civil structures, mining, and many more. In some disciplines, engineers use advanced numerical techniques, whilst in others, an engineer's job is to keep an operation running smoothly by preventing the breakdown of equipment. The common denominator of all such activities is engineers. Engineers are the thread that keeps beads of civilisation together. Their roles in their domain at the macro level are similar. This paper makes no distinction between various specialisations.

The term 'heuristic' is used as a label for procedures that are gained by experience and guides judgement in decision-making. Heuristics are commonly understood as rules of thumb procedures that may not lead to optimal or solutions but will generally produce outcomes that are 'good enough. It is also widely acknowledged that heuristics can result in systematic errors or biases. But all this is usually understood as a trade-off: heuristics forego optimal outcomes in favour of the economy. Systematic errors may result on some occasions, but they tend to produce satisfactory results.

A combination of both heuristic and numerical knowledge is used in the design and maintenance of engineering systems, as well as responding to emergencies such as oil spills, landslides, hurricanes, etc. Heuristics can also be used to decide on the layout of a system, then numerical knowledge is often used to conceptualize the complete system. Although experienced engineers know where to find information and how to make accurate computations, they also keep some amount of information in their brains for rapid recall, made up largely of shortcuts and heuristics.

Engineers are the prime tool of innovation of all ages. Thus, it is of interest to understand how engineers think, reason, and engage when using advanced analytical techniques and other tools to analyse and understand the demands of a situation. Engineers' roles are the prime influencer in all fields of human endeavour from aerospace to offshore to civil structure as well as just keeping an installation operational. To perform their tasks engineers, require more than analytical and numerical tools. They also rely on their intuition and learned experiences. The profession is not just to observe, collect and file data, but also to judge where the system is heading. For example, the job of an engineer in charge of a plant is not just to read dials and make a note of numbers, but to comprehend them and make a connection to the health of the system; and make a judgment if a runaway process is in progress. In such a context, expertise means how fast you can think on your feet.

An engineer in charge of preloading a jack-up in its new location does not model the operation using a powerful computer on the spot, even if he did, the results would be not very useful if the soil and weather conditions turn out to be different than predicted; the engineer must decide on what corrective action is required while the installation is still in progress. Similar uncertainty exists when a pilot tries to land a helicopter on an offshore platform when the weather is favourable. How do they do it?

This paper argues that the primary tools of engineering are heuristics, which are the experiences accumulated by many years of fieldwork, and possibly some by education. Koen [21] asserts: "*Engineering is the use of heuristics to cause the best change in a poorly understood situation within the available resources.*" This definition embodies two important concepts; first, engineers need heuristics, and second, problems requiring engineers' attention are generally too poorly defined to ignore heuristics. Though abstractions, analyses, and other cognitive tools may be used to obtain a better insight, the reality is too complex for full understanding. It is impossible to predict and assess every possible operational case and situation for a system over its life cycle. Koen [21] describes heuristics in this way: "*Although difficult to define, a heuristic has four definite signatures that make it easy to recognize: 1. A heuristic does not guarantee a solution, 2. It may contradict other heuristics, 3. It reduces the search time for solving a problem, and 4. Its acceptance depends on the immediate context instead of on an absolute standard*." Sometimes the rationale behind a heuristic is obvious e.g.: "Measure twice, cut once." Other times the rationale is more obscure such as "*Allocate resources so long as the cost of not knowing exceeds the cost of finding out.*" [21]

Experience shows that heuristic solutions work, but we do not have a mathematical proof for them. Heuristics are commonly defined as cognitive shortcuts or "rules-of-thumb" that simplify decisions, especially under time-limited conditions. However, heuristics can also lead to cognitive biases, which is discussed in Part IV. Simplify as the adage says, "you can't eat an elephant in one sitting". Simplifying is to strip out unnecessary so that you can see the necessary.

An analysis is performed to understand the problem you are trying to solve, the problem's environment determines what behaviours should the solution exhibit. etc. Analyses help to decide which heuristic fits best to the problem at hand. The term Analysis is used in this paper to mean the *investigation* of a problem and requirements, rather than a solution. For example, if a new highway is desired, then an analysis must identify which communities it would serve, what other facilities needed to enable its functionality? Analyses are for gaining gain insight and to understand what is needed to get more out of a solution. Engineers mostly refer to analysis as the process of applying mathematical models and other tools to find the answer to a question.

The term *Conceptual Design* refers to a *conceptual solution* that fulfils the requirements, rather than its implementation. For example, a concept is a complete listing, description, and order of all equipment required for a subsea production facility to function, but not their physical properties e.g., weight, size, footprint, etc. Conceptual design is deciding how to organize a solution based on a concept of operation once the requirements are understood [31].

Ultimately, a conceptual design must be detailed. The true and complete realisation of a concept is termed detailed design. Thus, detailed design is the creation of something which meets the specification of the concept, that is recreating something whose purpose and functionality have already been specified in some detail [34].

These four papers are structured as follows. Part I sets the scene by providing a discussion of the background principles that are relevant to engineers' decision-making, i.e., fundamental ideas and principles of rationality, and rational and critical thinking [2]. In Part II [35] two major research programs regarding heuristics lead by Kahneman [16] and Gigerenzer [10] are described. The findings of programs led by Kahneman and Gigerenzer are discussed. Part III [36] primarily deals with misconceptions in reasoning and biases when using shortcuts. Then, in Part IV [37], we discuss the appropriateness of heuristics for use in engineering. A discussion in Part IV [37] ties all these papers together and provides some overall conclusions.

2. Meaning of Rationality

The term rationality is taken to mean 'to act reasonably' as judged by peers, which is different from being logical which can be proven to be right or wrong using mathematics. Thus, rationality requires (a) a coherent worldview and what you want to achieve. Human judgments often deviate from logic but still can be rational. The so-called rational approaches to decision-making, in literature, make extensive use of logic, with theories based on axioms using mathematical models. As formality carries a connotation of being scientific, viewed from this perspective, rational approaches are thought to yield the best results. However, in a complex situation, such an approach is difficult to optimize due to many reasons including cognitive ability, time pressure, and data availability; thus, intuition would triumph in such situations [10].

In this four-part paper, rationality is defined as 'the ability to make reasonable judgments and decisions in time,' (which is different from intelligence), and can be improved through education and training, but intelligence is what one is born with, i.e., it is innate. However, going through the educational system does not guarantee that you are rational, just like going to church does not make you a Christian.

The concept of rationality is much more than the concept of intelligence since it does not stop mastery of facts that are achieved as thoughts. It is the ability to comprehend, and the capacity to evaluate the principles and purposes in the light of reasons; it implies consistent behaviour. Making a rational decision [33] means continual questioning to eliminate inaccuracies, wrong assumptions, enhance understanding, and strive for intellectually honest results; such combinations are very difficult to optimize when under time pressure and the situation demands a fast reaction. Rational thinking emphasises the ability to draw reasonable conclusions from data, rules, and logic, thus education and practice can increase rational thinking. But, if the environment changes, then a rational thinker may require a different skill set for the new environment. The logic used for sense-making of scientific experiments cannot be applied when buying a car or picking groceries from a supermarket shelf, which demands a different skill set and is termed "Rationality" in this paper. Learning to act rationally requires both practice and theory. Reading a car driving manual will not make you a driver, also just practicing will not either. One needs a correct blend of both. You need a good understanding of physics.

Engineers decide by combining rational analysis and gut feeling; the proportion depends on the task. Both decision-making tools are sound but are subject to errors in different ways. The primary emphasis of engineering education is on analytical ability, not much time is dedicated to scrutinizing the premises of the analytical method. When using these analytical tools an engineer needs to make a lot of subjective judgments (assumptions), such as properties, boundary conditions, loading, among others, i.e., relying on legs that can barely support the body. Dijksterhuis et al. [7] have studied the relative effectiveness of rational and intuitive decision processes, concluding that although rational procedures score better for simple decisions, the reverse is true where the situation is complex. Engineers have developed many methodologies based on experience to guide them in decision-making. Once engineers have experienced something, the mark will remain with them forever and shapes their next movie which will also be tempered with new experiences - this is the adaptive tool. They become adept at recognizing where each scheme yields the greatest benefit. Applying the correctly learned patterns provides a fast, efficient, and proven approach to problem-solving. Engineers as experts depend on their long-term memory, and their ability to analyse problems deductively, selecting and retrieving cues by recalling the appropriate patterns from memory, and correctly applying them to solve a problem. This paper calls such learned tools "heuristics", and engineers accumulate these in their decision-making toolbox. The use of heuristics by engineers is not limited to their professional life. "*At some (high) level of generality, there is considerable overlap in the way pretty much everyone interested in heuristics at all thinks about heuristics"* [20]. The issue is, where and how heuristics can be (and are) used in engineering, and whether there could be a set of heuristics that could be powerful aids in helping engineers to make good decisions in complex systems' context [8].

3. Critical Thinking and Emotion

Historically, critical thinking is limited to a subset of rationality which deals with identifying and avoiding fallacies, argument analysis, and evaluation, as well as on reasoned judgment. "*Rationality and critical thinking include things about deciding what to believe and what to do*" [2]. Critical thinking is the ability to think clearly and coherently, understanding the logical connection between ideas. In Siegel's [26] view, critical thinking is the same mental and psychological activity as rational thinking. He [26] defines a critical thinker as "*one who is appropriately moved by reasons, and he argues that this characterization can be used as that of a rational thinker without any modifications*." Hence, the notion of reason conceptually binds together critical thinkers and rational thinkers. This paper is not about critical thinking, but engineers should be critical thinkers to use heuristics correctly and in the right domain. Rationality engineering means taking a measured decision, which is not risk-free but aimed at achieving the desired goal while attempting to maximize gains.

The reason is rarely carried out without emotional influence. Emotion makes it difficult to objectively evaluate the situation [39]. Humans depend on "feeling" for their survival, which is as true as it now as it was for the first humans on earth. In this way, feelings are heuristics that have evolved by evolutionary processes and are not exclusive to humans. Simply by being aware of your tendency to be swayed by your feelings and emotions, you will be better able to make more objective and balanced decisions. We feel something "in our bones" or feel this is the correct outcome based on our emotions. Feeling leads to attachment which influences decision-making. Feeling gives the final push in decision-making, though the degree of its influence may differ. Learning through emotional fear is quick and sometimes effective, but "expertise" is a collection of micro-skills that are acquired through time, involving numerous encounters with fear.

Lehrer [22] relates the story of a patient he calls Elliott who lost the ability to decide, due to part of his brain removed to excise a tumour. The surgery eliminated his ability to "feel," leaving him completely rational but utterly unable to decide. Lehrer [22] notes that Elliott's inability to decide came down to a lack of emotion. "*It seems to make good decisions; one must learn to combine rational thought with emotional awareness*."

A celebrated case is *Phineas Gage*, age 25, the foreman of a crew who was cutting a railroad bed in Cavendish, Vermont USA, in 1848 [15[. On September 13, as he was using a tamping iron to pack the explosive powder into a hole, the powder detonated. The tamping iron shot skyward, penetrated Gage's left cheek, ripped into his brain, and exited through his skull, landing several meters away. Dr. John Martyn Harlow, who treated Gage for a few months, wrote "*Gage's friends found him no longer 'Gage'*; he *could not make decisions or plans*." Loss of the frontal lobes, which is associated with planning and intellectual strategies, has also an important role in emotion, which pushes one towards or away from a decision.

Human thoughts and actions extend beyond the narrowly defined notion of perfect rationality and are shaped by factors such as contextual cues, social norms, decision anchors, and selectively recalled feelings and experiences. These systematic patterns of deviation from classical notions of rationality are called 'cognitive biases' which influence what people view as rational. If overlooked, these processes can lead to erroneous decisions. Engineers as rational thinkers are also subject to cognitive biases (See Part II, 35). It worth remembering that instinct and emotion are at the basis of all decisions, actions, values, and world outlook. Reason and rationality are used to justify.

4.Engineering Rationality

There are limitations on people's ability to make 'Rational' decisions in every situation for a variety of reasons, including cognitive capacity and time pressure. One such limitation is understanding probabilities and frequencies (see part IV, 37). Humans can have a reasonable understanding of the frequency of an event (how often an earthquake with a certain magnitude would occur), but not as good an understanding of probabilities (the likelihood of an earthquake in their locality). Another issue is that humans fear a loss more than relish an equivalent or greater gain. For instance, most people would refuse a gamble in which they could earn $11 if a coin lands on heads but lose $10 if it settles on tails. People will often choose to avoid such a bet because the potential pain of losing often outweighs the pleasure of winning. Playing this game just once is a gamble, but if it is repeated then it becomes less of a gamble. Rejecting such a gamble is not a sign of humans' inability to think rationally. Becoming a more rational thinker in every domain is not feasible, thus humans settle on the best results by focusing on the things they value most [27]. Rational decisions are based on verifiable facts, reproducible data, and principles of logic, however when the emotional content of a situation is high, then emotions have their say. Herbert Simon in 'Reason in Human Affairs' book [28] wrote: "*To have anything like a complete theory of human rationality, we have to understand what role emotions play in it*," Emotions are needed to make a decision. When we are thinking about thinking, we are thinking about feeling [38].

Engineering rationality is the reasoning that leads not to abstract knowledge, but to knowledge-enhanced know-how, which is employed to solve problems. Thus, engineering reasoning is explicitly based on values, which are intrinsic to what will constitute an acceptable solution. Human values influence which issue is important, and hence affect their decisions. However, values are just one among several influencing factors, but they may be the dominant factor that will define the boundaries of involvement and the facts that humans consider relevant. We need to ask ourselves a set of exhaustive questions to make it transparent which elements should or should not be considered as relevant to the situation encountered. The rationality of engineering reasoning is measured by how the results of that reasoning 'work', are judged relative to a set of subjective value judgments [3] By asking questions you can turn data into information.

The rational engineering method may be defined as the use of heuristics to obtain the best results in an inadequately defined situation using the available resources. The term heuristic, in this definition, refers to anything helpful, useful, and based on experience, but it can be unjustifiable, and potentially fallible. Engineering heuristics involves graphs, mathematical equations, and empirical correlations used by the engineer while exercising their profession. They also include strategies used to reduce risk, allocate resources, and establish the approach required for problem-solving. A single heuristic is seldom used in isolation, but most often several heuristics are used in groups. The term "Best Engineering Practice" refers to the best collection of heuristics in the engineering community, which also includes analytical procedures.

A young recently trained analyst may be adept at solving well-defined technical problems but may not find a path through an ill-defined problem with multiple dimensions and issues, compared with a seasoned supervisor. The supervisor, in turn, understands the questions that need answering but does not understand the quantitative techniques required to find an answer, and so must take on faith, and approve, that the quantitative approach chosen by a junior is technically correct and that the young engineer's results are sensible. In such a situation a supervisor devises heuristics that make sense and what should be considered suspicious. Such heuristics maybe "Back of an Envelope Calculations" for sense-making to gain confidence in the technical ability of a junior colleague.

The thing that is called engineering judgment [32] has an important role in the engineering profession. Engineering judgment is learned and used as an experience-based yardstick, which is acquired by integrating diverse evidence into making a sound decision. In many situations, this form of engineering judgment, which is inferred from complex evidence, is an important resource for the decision-maker, especially when there is not much objective evidence. This dependence on judgment is especially evident in an emergency where a situation evolves fast, and a decision must be made under a time constraint. Evidence-based decision-making is not about prediction but for understanding and explanation as to why you came up with a certain conclusion. Only inquiring mind solves problems. The "Just do it" mantra most likely would lead you to a mess that you cannot climb out of. You need to think about which mess to jump in (*think before you jump*)- choose your own mess. Engineering judgment is a heuristic that has an essential role in the assessment. Experimental research about the way humans think, and how humans integrate evidence, as well as the performance of experts in tasks requiring engineering judgment, supports the belief that the ability of 'experts' to judge accurately may be overrated.

5. Heuristics

Engineers' decision-making is not entirely based on analytical fact, but intuition and employing methods that have worked before. Every engineering decision is essentially a problem-solving process. A civil engineer provides tangible, technical solutions to situations that demand answers to satisfy an identified need, for example, a building or a bridge. Engineers can be defined as problem solvers, from the viewpoint that engineers are responders to human technical needs.

The common major steps in decision making are [25]; "

- *Stating the problem (what is the right question)*
- *Developing a plan, i.e., the strategy (How to solve it)*
- *Implementing the plan i.e., idea generation; (What are viable solutions)*
- *Comparing solutions and pick the most promising one; (Why is this the right solution)"*

The emphasis of the process, as detailed above, is on applying rigorous and logical deductions to complex and ill-defined situations to obtain sound solutions. However, there are many situations where it is difficult to follow this process fully, for example, situations where a decision must be made in a limited time. Proficient engineers make decisions by using their experiences to recognize patterns and recall actions for situations that worked in the past.

George Polya in his book, *How to Solve It* [25], revived the heuristics concept to help students develop their thinking abilities to enhance problem-solving abilities. He defined the concepts and strategies of heuristics as:

"*Heuristic reasoning is reasoning not regarded as final and strict but as provisional and plausible only, whose purpose is to discover the solution of the present problem ... We shall attain complete certainty when we shall have obtained the complete solution, but before obtaining certainty we must often be satisfied with a plausible guess. We may need the provisional before we attain the final. We need heuristic reasoning when we construct a strict proof as we need scaffolding when we erect a building*." [25]. People reason from a set of premises and only consider possibilities that they believe to be compatible. Several possibilities are generally considered and among them pick the one which fits best with the situation.

In some cases, problem-solving may end up in complete certainty. However, problems often require a large mental effort commensurate with their complexity. Although, heuristic reasoning may be sufficient, but for problems requiring certainty, heuristics may only be a means to an end. Polya's [25] heuristics view complements the ideas of Simon's [29] which he called "Satisficing". Simon considers that " *the real-world solutions are often not reached by rationality, probabilistically, or recursive optimization, instead the decision-maker deems a solution as sufficient since the decision-maker has neither the time nor the wits to discover an 'optimal path', and the primary concern of a decision-maker is only to find a choice mechanism that would lead to a 'satisficing' path, a path that will permit satisfaction at some specified level of needs*" [27]

Simon [29] incorporated Polya's [25] heuristic concepts into a framework where problem-solving includes both the decision-maker and the environment where the decision is made. Gigerenzer and Todd [11] build upon Simon's work and contrasts the concepts of "Unbounded Rationality" and "Ecological Rationality". Unbounded rationality, as described by Todd and Gigerenzer [30] assumes a completely logical solution exists and that a solution can be found, or as Polya [25] said, "*a solution of complete certainty."* However, often there are insufficient resources to find a solution of complete certainty. Furthermore, the environment in which one operates may not permit a solution with certainty. The environment may limit the number of outcomes that are discoverable with heuristic thinking. This is a bounded solution, which Gigerenzer and Todd [11] called "Ecological Rationality" and Simon termed as "Satisficing". Engineers often work in an environment with limited resources and in several dimensions, including time and information. In this environment, it is not always possible to attain a theoretically certain solution, but only a plausible solution is possible, based on a bounded view of rationality [1]. Bounded rationality, satisficing, ecological rationality, and heuristics can be defined by Naturalistic Decision Making (NDM) [19]. Klein [17,18] defines NDM as *"the study of how people use their experience to make decisions in field settings. We try to understand how people handle all of the typical confusions and pressures of their environments, such as missing information, time constraints, vague goals, and changing conditions*".

Solution generation is the stage where engineers consider multiple options. It occurs throughout the decision-making process as solutions are developed and refined. For the initial idea generation, the goal is to explore, in both depth and breadth, the solution space. As the engineer explores solutions, heuristics are used to help generate solutions. Multiple heuristics may be employed within a single solution, and each heuristic can be applied repeatedly to transform the existing solution. Heuristics can focus on the form or the execution of an idea. The form tells us how a solution looks like, and the execution explores how to implement it.

A problem is defined as a situation that needs mental effort to create and/or select a transformation to a goal situation while observing a specific set of constraints. There may be some problem over how engineers use and select heuristics and their relevance for the situation at hand. This should be expected as heuristics are the result of experience and how they evolved. Thus, heuristics are context-dependent, intuitive, learned knowledge, or experiential understanding, which provides directions to enhance the chance of reaching a satisfactory solution, but not necessarily the optimal one. Experience leads to new truths that knowledge has not been able to reach. "*Knowledge is knowing a tomato is a fruit; experience tells you not to put it in a fruit salad"* (*Miles Kington, British journalist 1941-2008*). This quote means, a wise fool gains knowledge but has not yet acquired the wisdom, to apply it correctly. He/she knows enough to sound smart, but not enough to be wise. Charles Spurgeon (1834 –1982), was an English Particular Baptist preacher) once said, "*Wisdom is the right use of knowledge. To know is not to be wise. Many men know a great deal and are all the greater fools for it. There is no fool so great a fool as a knowing fool. But to know how to use knowledge is to have wisdom*."

Heuristics are both window and mirror; a window to look outside and a mirror to see yourself. If you think the concept of the window too restrictive, then think of it as a sliding door through which you can get out to enrich your experience or invite others in to draw on their experiences.

"**Common sense**" is a **heuristic** that is used for decision-making based on one's observation of a situation, as well as in the sense of being right and fair. This is a practical and prudent method that can be applied where the right and wrong answers are relatively distinct. Common sense is inborn rational thinking that is passed down by generations either genetically or by learning. Common sense incorporates thinking skills developed from logic, intuition, and the human capability to observe events and absorb lessons and information. Intuition is nothing more than recognition and hence most useful in repetitive tasks.

Proverbs, as suggested by Polya [25], works like heuristics but should be used with caution. He wrote: "*It would be foolish to regard proverbs as an authoritative source of universally applicable wisdom, but it would be a pity to disregard the graphic description of heuristic procedures provided by proverbs" (1985, p. 113).* Numerous proverbs are remembered by engineers. "Measure it twice and cut once". " It is not things you don't know that kills you, it is the things you know but it ain't so"; "You can't chew with somebody else's teeth": "no one would scratch your back except your fingernail"; "can't see the wood for the trees."

The analogy is another heuristic that is commonly used to draw inferences between similar events. The understanding of analogy is important since, " ... *people often use vague, ambiguous, incomplete, or incompletely clarified analogies*" [25]' Like other cognitive models, overt awareness of usage helps to avoid misuse and capitalizes on strengths, "*It would be foolish to regard the plausibility of such conjectures [analogy] as a certainty, but it would be just as foolish, or even more foolish, to disregard such plausible conjectures*" [25]. Analogies are used in science to gain insights into phenomena that are usually unobservable. "*In science, two systems are analogous if they agree in the relations between their respective parts. Analogies are fundamental to the development of new ideas and the lifeblood of human thinking*" [4]. However, taking an analogy literally can be misleading.

The problem is how to be sure that our analogies are a good "fit" for the current situation. Thus, we need to bring rigor to our intuitions and mitigate the impact of flawed memory, heuristics, and cognitive biases?

Neustadt and May [24] suggest the following approach:"

- *Write down a list of not only the similarities in a situation that are considered analogous to your experience but also the differences.*
- *List what is known, unknown, and presumed about the situation.*
- *Share this appreciation with others and invite them to challenge it."*

Axillary elements were introduced by Polya [25] is "*An element that we introduce in the hope that it will further the solution is an auxiliary element"*. An example of adding an auxiliary element is superimposing of directions on the map in satellite navigation, which is further enhanced by verbal descriptions.

Mnemonic is a memory aide for information retention or retrieval. Numerous mnemonics are devised for different professions. For example, the mnemonic CURVES: (Choose and Communicate, Understand, Reason, Value, Emergency, Surrogate) addresses the abilities that a patient must possess to have decision-making capacity, as well as the essentials of emergency treatment. Table 1 [5]. This may be used, albeit with some modification in providing emergency relief to victims of a disaster.

Table 1 A Mnemonic Suggested for Providing Emergency Treatment in an Acute Setting [5]

C: Choose and communicate. Can the patient communicate a choice?
U: Understand. Does the patient understand the risks, benefits, alternatives, and consequences of the decision?
R: Reason. Is the patient able to reason and provide logical explanations for the decision?
V: Value. Is the decision in compliance with the patient's value system?
E: Emergency. Is there a serious and imminent risk to the patient's well-being?
S: Surrogate. Is there a surrogate decision-maker available?
Source: CURVES: A Mnemonic for Determining Medical Decision-Making Capacity and Providing Emergency Treatment in the Acute Setting. Chest. 2010;137:421-7.

Another example is DESIDE (Detect, Estimate, Set safety objectives, Identify, Do, Evaluate) [23], which has been demonstrated to significantly improve military pilots' in-flight decision-making performance'; Table 2. There are numerous mnemonics for decision-making in fast-moving situations. Decision-making requires sense-making i.e., how to size up a situation, which is the result of many years of learned experiences.

Table 2 DESIDE Mnemonic to Improve In-flight Decision-making Performance.

Detect: The decision-maker may or may not detect that a change in the expected outcome has occurred.
Estimate: The decision-maker may or may not estimate the need to react to the change
Choose: The decision-maker may or may not choose a desirable outcome, in term of success for the flight
Identify: The decision-maker may or may not try to identify actions that could be successfully counter the change
Do: The decision-maker may or may not do something positive to adapt to the change.
Evaluate: The decision-maker may or may not evaluate the effect of the action in the previous step.

Decomposing and recombing: Engineers generally break down a complex problem into smaller chunks, whose solutions are either known or may be readily found; this is known as the "Reductionist Approach". In designing complex structures or ideas, engineers will often break these down into smaller, simpler parts, find a solution for each part, and assemble these solutions to obtain a solution for the whole. This may not be possible when time is at a premium. The real challenge is when "*Too many or too minute parts are a burden on the mind. They may prevent you from giving sufficient attention to the main point, or even seeing the main point at all*" [25].

Enrico Fermi used to challenge his students with problems that seemed impossible. One such problem was that of estimating the number of piano tuners in Chicago given only the population of the city.

A typical solution involves breaking down this problem into simpler problems that would involve multiplying together a series of estimates that would yield the correct answer if the estimates were correct.

For example, we might

make the following assumptions:

1. approximately 5,000,000 people are living in Chicago.

2. On average, there are two persons in each household in Chicago.

3. Roughly one household in twenty has a piano that is tuned regularly.

4. Pianos that are tuned regularly are tuned on average about once per year.

5. It takes a piano tuner about two hours to tune a piano, including travel time.

6. Each piano tuner works eight hours a day, five days a week, and 50 weeks a year.

From these assumptions, we can compute that the number of piano tunings in a single year.

in Chicago is: (5,000,000 persons in Chicago) / (2 persons/household) × (1 piano/20

households) × (1 piano tuning per piano per year) = 125,000 piano tunings per year in

Chicago.

And we can similarly calculate that the average piano tuner performs: (50 weeks/year) × (5

days/week) × (8 hours/day)×(1 piano tuning per 2 hours per piano tuner) = 1000 piano

tunings per year per piano tuner.

Dividing gives: (125,000 piano tuning per year in Chicago) / (1000 piano tunings per year

per piano tuner) = 125 piano tuners in Chicago.

This method does not guarantee correct results; but it does establish a first estimate which might be off by no more than a factor of 2 or 3--certainly well within a factor of, say, 10. We know, for example, that we should not expect 15 piano tuners or 1,500 piano tuners.

6. Mental Model for Reasoning

A mental model is our perception of reality. Once it takes hold, we may believe it is a good match of reality. There are many ways to form flawed models of reality. We see the world much more coherently than relay is. Engineers conceptualize something which does not yet exist, which requires intuitive leaps. For such a leap of imagination, engineers need Mental Models to make better decisions. Heuristics are part of many Mental Models. However, sometimes the answer you are seeking requires knowledge beyond what you know, or heuristics can tell you. Heuristics that come from a wide range of disciplines such as psychology, physics, statistics, and behavioural economics, are useful to analyse problems from different perspectives.

A Mental Model is a representation of a domain to understand how something works and or how someone reasons. Mental Models allow reasoning about a situation without having direct experience of it. They are based on generalizations and analogies which may or may not be accurate; while heuristics are a set of rules-of-thumb, methods, or strategies used for decision making. A heuristic to open a door could be to push against the door, while another could be to add your body weight as well. Another example is when you exit a room that has a handle on it, do you push it or pull it? Heuristics tell us that handles are made for pulling.

Humans do not think in mathematical terms but create a simple narrative for everything that requires making sense of it; call it a Mental Model. If the constructed narratives deviate too much from reality, realism gets lost in the decision-making process, and when you venture too much beyond the borders of reality, your perception of the world is flawed, while you may still believe in your narrative. Humans in constructing their stories need causation and they see a causal relationship where there might be none. Engineers must find lots of information and weave it together to come up with a coherent narrative.

Human reasoning does not work like proving a logical problem; it is unstructured and sometimes goes around the houses. Mental Models have roots in attitudes, such as beliefs, ethics, expectations, and values that allow individuals to function as they do. You exploit what you know and do not differentiate between deduction, induction, and abduction, namely you conclude things based on what you think you know. Mental Models are constructed using all possibilities and conclusions are drawn from these models. Looking at it this way, the reasoning is a simulation of the world constructed with what you know and believe to be true, without using a formal logical argument. The two elements of the above definition are:

1. Mental Models are based on belief, not facts. A Mental Model is what we think how a system works.

2. Individuals have their Mental Models, which are internal to their mind, and.

3. Different people will possibly construct different Mental Models of the same system's working.

Mental models are the framework of human reasoning. They simplify complexities to a level that the brain can cope with. People use Mental Models for decision-making without the need to know everything about that system. Mental Models are influenced by the brain's dual processes. System 1 (Type 1 Thinking) does not give time for Mental Models to be checked for biases. However, it is possible to escape the attraction of Type 1 Thinking, by keeping impulses in check, listening to System 2, and reading between the lines. It is not the maximum intelligence one must strive for but avoiding repeating the same mistake.

Mental Models are like conceptual drawings of a system, which is an abstraction of reality; it looks like reality, but it is not a replica. Details are left out so that they do not obscure the underlying idea, hence consequently can be useful. They are simplifications of what they are supposed to represent. A drawing can also be a snapshot of a concept at a point in time, which subsequently has been changed. Mental Models help to perform mental stimulation, or thought experiments, to examine what can be known or when to investigate the nature of things and answer "what-if" questions.

Kenneth Craik [6] suggested that the mind constructs "*small-scale models of reality that it uses to anticipate events."* That is, a Mental Model is a kind of internal representation of external reality, hypothesized to use in reasoning, and decision-making. Jay Wright Forrester's [9] definition of a Mental Model is: "*The image of the world around us, which we carry in our head, is just a model. Nobody in his head imagines all the world, government, or country. He has only selected concepts, and relationships between them, and uses those to represent the real system."*

According to Johnson-Laird [12] "Mental Models can be constructed from perception, imagination, or the comprehension of discourse", which is like engineering drawings of structures, which are like the structure that they represent.

Mental Models are based on a few axioms (assumptions). Each Mental Model is a representation of a possibility of capturing what is common to all the different ways in which the possibility may occur [14]. They typically represent only those situations that are possible. However, they also can represent what is assumed to be true. According to Johnson-Laird [13], everyday reasoning depends on the simulation of events in Mental Models The principal assumptions of this theory are:

- Each model represents a possibility.
- Models are iconic insofar as possible.
- Models explain deduction, induction, and abduction.
- The Mental Model theory gives a 'dual process' account of reasoning.
- The greater the need for more alternative models the more is the likelihood of error.
- Mental Models represent only what is possible.
- The meanings of terms such as 'if' can be modulated by content and knowledge.

As discussed previously, the world is a patchwork of systems; large and small. Each of these systems consists of multiple inter-dependent parts which are organized in a particular way to achieve the required function. Systems Thinking is the lighthouse when navigating through a stormy sea; it forces you to consider different disciplines. Paraphrasing Ackoff:

"Disciplines do not constitute different parts of reality; they are different aspects of reality, different points of view. Any part of reality can be viewed from any of these aspects. The whole can be understood only by viewing it from all perspectives simultaneously.

Considering again the car, which is a system. It has many parts that depend on each other to enable the car to function. You wish to understand how it works and which part you can remove without affecting its functioning. You may jump into this decision-making process and remove a part that you believe is superfluous and see where your decision takes you. Alternatively, you may use your intuition shaped by past experiences, and perhaps other advice that is available to you. This is a better approach than blindly jumping in, but not by a large margin. The answer to what is the correct decision lies in Mental Models, and a disciplined approach to their use. You need a Mental Model to appreciate the role of each part and how they hang together to deliver a function. To create a Mental Model for the task, start with asking:

- What is the function that the system delivers?
- How are components arranged and relate to each other within the system?
- What are the underlying principles behind the functioning of the system?
- Can the same function be delivered differently?
- Can the identified principles be used differently?
- Is this system efficient yet?

Russell Ackoff asserted that "*The performance of a system depends on how the parts fit together, not how they act when taken separately."*

In most cases, it is just one of a system's parameters that are constraining the system from achieving a greater total output. Therefore, identifying the controlling constraints by trial and error would increase a system's output by identifying and addressing the constraining parameter. In an iterative improvement, you may not be able to bring the system to your desired level of efficiency, or you may hit an impasse. It is then time to abandon and change direction. Use nothing but the proven, underlying principles.

When we make decisions, we rely more on intuition than on deliberation (Part II). In Type I reasoning, our intuitions make no use of working memory and create a single model. But intuition is not always enough for rationality, thus a single Mental Model may be the wrong one.

The more models you have—the larger is your toolbox—the more likely you are to find a suitable model to fit your decision-making requirement. Awareness of cognitive biases in thinking could assure fewer systemic errors in thinking. Most engineers carry more mental models in their heads than a scientist, who is a specialist. This patchwork of Mental Models enables engineers to see things from different angles. A typical engineer will think in systems by default.

Not all decisions are worth agonizing over. Are we improving the colour of the upholstery or the fuel efficiency of a car? The amount of effort must be on par with its return. You can improve on your effort and consider the car itself. Working hard when there is something with more value to work on, is the dictate of Type 1 Thinking. Enjoying the flow of the puzzle but avoiding addition. The objective of continual use of Mental Models is constantly adjusting the decision trajectory. You form an opinion by considering outputs only, but you can also form a strategy if you look at the world as a patchwork of systems. Optimizing systems to get more out of them, and making good decisions are two pillars of Mental Models. Good decision-making may occasionally require silencing System 1 Thinking and switching to System 2, which is about Mental Models.

At a certain point, the incremental benefits you get from analysing a decision will get increasingly smaller. When you are hungry the first sandwich gives you satisfaction, but the satisfaction from the second sandwich will not be as much. This concept applies to engineers in several ways. First, make sure you are focusing on the most critical demand. As crucial as detailed data collection is, knowing when to call it complete is more important. The outcome would probably not be doubled by spending twice as much time on data gathering, and as details get more trivial, the less those details will impact the outcome. There are diminishing returns to gathering obscure details, and the sooner you notice them, the sooner you can concentrate on what matters.

The concept of "Safety Margins" is to leave room for errors and to avoid a total loss. It is better to be pleasantly surprised than proven wrong.

We design systems with redundancy, to protect against failure. This drastically reduces the chances of total loss. The system may sustain some loss, but if it does not break you back, you can stand up again.

Mental Models are a decision-makers toolbox. You need to pick the right tool to suit the problem at hand. You need more tools to solve a wider variety of problems. On the other hand, using more Mental Models to solve a problem enhances certainty, since a theory may turn out to be wrong one day.

Upon taking up a problem your understanding keeps enhancing. With this newly gained knowledge update your Mental Models and see if they still suggest you are moving in the right direction and answering the right question. As the world around us moves forward, there is a need to revisit some past decisions. If you do not change your mind occasionally, you end up spinning on the spot.

There are many types of Mental Models, and each takes a unique approach to reduce complexity. We need simplification to make sense of the world around us and to make good decisions. Each Mental Model provides a kind of framework for looking at problems. To improve your problem-solving ability, you need a larger toolbox of Mental Models, giving you more options to come up with the right answer.

A patchwork of Mental Models allows us to adjust our views of a challenge if we need to. After all, not every dilemma is presented to us in the same way or can be decided on from the same vantage point. The more Mental Models you experiment with, the more adaptable you will become to the challenges coming your way. Where do you begin to build your patchwork of Mental Models? A few of the most common Mental Models are listed below, you might be using them without knowing.

Pareto Principle is a good Mental Model. This principle says 80% of your output will come from 20% of your inputs. Substitute different words for output and input. For example, 80% of your income will come from 20% of your efforts. Looking at outputs only (the result of a decision), you can form an opinion as to where your decision-making is taking you. Thus, by looking only for the output you can not only strategize, but you can also form an opinion.

Regret Minimization, namely choosing an option that you would most regret not adopting when looking back after the dust has settled.

Inversion Perspective, that is instead of thinking about the desired outcome, consider outcomes that you should avoid. For example, in a decision-making situation, instated asking yourself "what action should I take to get a favourable outcome", ask yourself "what are the top 5 things which would impact my decision negatively", then make sure to avoid them. Avoiding stupid decisions is easier than getting a brilliant outcome. You may not always make a good decision by inverting the problem, but surely you will improve it.

Reverse-Engineering is disassembling a system to understand how its elements relate to each other, and what function they deliver. This is to enhance the system, copy it, or re-engineer it. In decision-making, untangling threads of thought leading to a decision helps to clarify and separate the underlying ideas or facts from assumptions. After stripping out all the add-ons, what remains are the essentials. Aldus Huxley said, "fact *doesn't cease to exist if we ignore it*."

Algorithms are a sequence of steps, that one needs to follow, to get to an answer or set of actions resulting in the desired outcome. This is stated in the form of a series of "If-Then" statements.

Chain of Events: In risk analysis models, the chain events are constructed (known as Fault Trees and Event Trees) to study which events would lead to what accident, and then to erect barriers along the path to prevent it. Chain of Events modelling is intrinsic to forensic engineering and accident investigations, where failures are analysed for the root cause or causes. Only when failures have been investigated with conclusive results can remedial action be taken with confidence. There are several chains of events models and among them, Reason's Swiss cheese model is the most popular one.

Remembering isolated facts and heuristics and trying to fit them into a decision-making situation will not work if the facts are not woven into the fabric of a plausible theory, or those facts are not in a usable form. The fabric of Mental Models permits us to adjust our view of a situation if we need to. Not every dilemma presents itself in the same way or can be decided on from the same frame of mind. The more Mental Models you experiment with, the more adaptable you become to the challenges that come your way.

Mental Models are not a replacement for evidence-based engineering. Their biggest potential lies in how they help us navigate the world by creating meaningful and repeatable abstractions, so we can make better choices without reaching decision fatigue. Mental Models should be evaluated based on how useful they are, not by being right. The effectiveness of Mental Models requires scepticism, not cynicism, to succeed.

7. Conclusions

The objective of this series of papers is to advance knowledge of heuristics for engineers. The focus of this part is to provide background information and definitions of the terms used.

In a dynamic and uncertain environment, seeking an optimized solution is often difficult if not impossible. Confronted with this, engineers use heuristics to make decisions within reasonable time and effort. Heuristics can also help engineers to save time and mental energy, by freeing up cognitive resources for more complex planning and problem-solving endeavours.

Many commonly used heuristics are defined in this paper. Since heuristics are experienced-based (self or others) they are primarily valid only for a specific environment. Engineers may unwittingly commit an error, known as bias when using heuristics. Several biases, along with how to avoid them, are discussed in Parts II and IV. In literature, heuristics are identified by the errors (biases) they cause, thus the terms *heuristic* and *bias* became almost synonymous and sometimes are used interchangeably.

Acknowledgments The authors would like to thank Chris Millyard, Sassan Rezaei, Mehrdad Rahbari, Kabir Sadeghi, and Michael Vigne, Mohsen Mirza, Giles Thompson for their counsel and feedback, who have assisted to improve the quality and integrity of these papers. I am very much indebted to Mehrdad Rahbari for his patience and help with improving successive revisions.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

8. References

1. Barros, G., (2010). Herbert A. Simon and the concept of rationality: Boundaries and procedures, Brazilian Journal of Political Economy, vol. 30, nº 3 (119), pp. 455-472.
2. Battersby, M, and Bailin, S. (2018). Inquiry: A New Paradigm for Critical Thinking, Windsor Studies in Argumentation Vol. 7.
3. Bazerman MH: Judgment in Managerial Decision-Making 4th edition. New York: John Wiley and Sons; 1998.
4. Brown, S., and Salter, S. (2010). Analogies in science and science teaching, Adv Physiological Education 34: 167–169.
5. Chow GV, Czarny MJ, Hughes MT, Carrese JA. CURVES: a mnemonic for determining medical decision-making capacity and providing emergency treatment in the acute setting. Chest. 2010 Feb;137(2):421-7.
6. Craik, K. (1943) work entitled *The Nature of Explanation*.
7. Dijksterhuis, A., Bos, M.W., Nordgren, L.F., and van Baaren. R.B., (2006). "On Making the Right

Choice: The Deliberation - Without - Attention Effect." Science 311: 1005–1007

8. Elms, D. G., and C. B. Brown. 2013. "Intuitive Decisions and Heuristics – An Alternative Rationality." Civil Engineering and Environmental Systems 30 (3-4): 274–284.
9. Forrester, J. W. (1971) Counterintuitive behaviour of social systems. Technology Review.
10. Gigerenzer, G. (2008). Why Heuristics Work. Perspect. Psychol. Sci. 2008, 3, 20–29.
11. Gigerenzer, G., Todd, P.M., & the ABC Research Group., (1999), Simple heuristics that make us smart. New York: Oxford University Press.
12. Johnson-Laird, P.N. (1983). *Mental Models: Towards a Cognitive Science of Language, Inference, and Consciousness.* Cambridge: Cambridge University Press.
13. Johnson-Laird, P.N. (2006) How We Reason. Oxford University Press
14. Johnson-Laird, P.N., and Byrne, R.M.J. (2002) Conditionals: a theory of meaning, inference, and pragmatics. Psychol. Rev. 109, 646–678
15. Kean, S. (2014). "Phineas Gage, Neuroscience's Most Famous Patient". Slate. Reprinted in Skloot, Rebecca, ed. (2015). The Best American Science and Nature Writing 2015. Houghton Mifflin Harcourt. pp. 143–8.
16. Kahneman, D. 2011. Thinking, fast and slow. New York: Macmillan.
17. Klein, G. (1989). Strategies of decision making. Military Review, 56, 56–64.
18. Klein, G. (1993). A recognition-primed decision (RPD) model of rapid decision making. In G. Klein, J. Orasanu, R. Calderwood, & C. E. Zsambok
19. Klein, G. (2015). A naturalistic decision-making perspective on studying intuitive decision-making. Journal of Applied Research in Memory and Cognition, 4, 164–168.
20. Kelman, M. (2011). The Heuristics Debate. Oxford: Oxford University Press.
21. Koen, B. V. (2003). Discussion of the Method Conducting the Engineer's Approach to Problem Solving 276 pages
22. Lehrer, J., (2009). How Do We Decide, Houghton, Mifflin, and Harcourt publishing?
23. Murray, S.R. (1997), ' Deliberate Decision Making by Aircraft Pilots: A Simple Reminder to Avoid Decision Making Under Panic', The International Journal of Aviation Psychology, Vol. 7, No. 1, pp. 83-100.
24. Neustadt, R, and May, E (1986) Thinking in Time: The Uses of History for Decision Makers. New York: Free Press
25. Polya, G, (1945). How to Solve It: A New Aspect of Mathematical Method. Newest edition 2014, Princeton Science Library.
26. Siegel, H. (1980). Critical Thinking as an Educational Ideal, The Educational Forum 45(1):7-23
27. Simon, H. A. (1956). Rational choice and the structure of the environment. Psychological Review, 63, 129–138
28. Simon, H., (1983). Reason in Human Affairs, Stanford University Press; New e. edition (30 Jun. 1983), 128 pages
29. Simon, H.A. (1991). Bounded Rationality and Organizational Learning. Organization Science 1991, 2:125-135.
30. Todd, P. M., Gigerenzer, G., and the ABC Research Group (2012). Ecological Rationality: Intelligence in the World. New York, NY: Oxford University Press.
31. Yasseri, S., (2014), Application of systems engineering to subsea development, Underwater Technology: The International Journal of the Society for Underwater 32(2):93-109, DOI: 10.3723/ut.32.093
32. Yasseri, S., (2015), Evidence-based practice in subsea engineering Underwater Technology, The International Journal of the Society for Underwater 32(4)
33. Yasseri, S., (2017), Thinking Like an Engineer, available on ResearchGate https://www.researchgate.net/publication/319644185_Thinking_like_an_engineer
34. Yasseri, S and Bahai, H. (2018), Availability assessment of subsea distribution systems at the architectural level, Ocean Engineering, 153, 399-411
35. Yasseri, S., (2021), Rationality for engineers, Part II, IJCOE Vol.4/No. 2/Summer 2020 (1-13)
36. Yasseri, S., (2021), Rationality for engineers, Part III, IJCOE Vol.4/No. 2/Summer 2020 (1-13)
37. Yasseri, S., (2021), Rationality for engineers, Part IV, IJCOE Vol.4/No. 2/Summer 2020 (1-13)
38. Zajonc, R.B. (1997). Emotions, In D.T. Gilbert, S.T. Fiske, & G. Lindzey. (Eds.), Handbook of Social Psychology, Fourth Edition (pp. 591-632). New York, NY: Oxford University Press.
39. Zajonc, R. B. (1980), Feeling and thinking: Preferences need no inferences. American Psychologist, 35(2), 151-75.

Available online at: www. Ijcoe.org

Application of Fuzzy Cognitive Map to Design the Causal Structure and Analyze the Factors Affecting Good Governance in the Ports and Maritime Organization

Ahmad Ghafarzadeh [1], Gholamreza Memarzadeh Tehran [2*], Naser hamidi[3], Nabiollah Mohammadi[4].

[1] *PhD Student, Department of management, Zanjan Branch, Islamic Azad University, Zanjan , Iran.*
[2*] *Associate Professor, Department of management and Economic, Science and research branch، Islamic Azad University, Tehran, Iran (Corresponding Author).Email: Gmemar@gmail.com.*
[3] Associate Professor, Department of management, Qazvin Branch, Islamic Azad University, Qazvin, Iran.
[4] Assistant professor, Department of management, Zanjan Branch, Islamic Azad University, Zanjan, Iran.

ARTICLE INFO

Article History:
Received: 06 Mar. 2021
Accepted: 30 May 2021

Keywords:
Governance
Good Governance
Fuzzy Delphi
Fuzzy Cognitive Map
Ports & Maritime Organization

ABSTRACT

Ports always play a strategic role in the development of a country's domestic and international trade, whether it is developing or developed. Ports as a base of maritime trade have changed a lot in recent decades, but in line with these changes, the Ports and Maritime Organization, as the main custodian of port and maritime policy, must adapt quickly, and this adaptation and the process of change in the next generations of ports of the country should lead to good governance in the management of port affairs. The evolutionary process of port governance shows that a single version cannot be used for governance reforms in all ports of the world, so in this study we try to examine the factors affecting good governance at the organizational level. The present study is a descriptive-survey research in terms of applied purpose and based on its nature and method. The statistical population in this study includes 22 experts of the Ports and Maritime Organization and the sampling method is random and purposeful due to the large number of experts. In this study, we first identify the factors affecting good governance by examining past literature studies in a hybrid manner and then examine the components by surveying experts using the Fuzzy Delphi method and finally to show the causal reasoning between the components of the technique. Fuzzy Cognitive Mapping is used. Findings indicate that the components of Equal Rights and Equity, Responsiveness & Accountability, Defining Outcomes have the highest degree of centrality, respectively, and this indicates the importance of the above components compared to other components of good governance in the Ports and Maritime Organization.

1. Introduction

According to global statistics, about 90% of the import and export activities of countries and in general loading and unloading activities, as well as 90% of the volume of goods transport in the global trade process are done by sea and ports. Therefore, from this perspective, it can be said that ports have a vital and fundamental role in this process. Therefore, due to Iran's location in the path of international corridors, its special strategic position and having about 3,000 kilometers of water borders in the north and south, this country has a privileged position in international transportation [1].
Thus, it is clear that ports always play a strategic role in the development of a country's domestic and international trade, whether it is developing or developed. Ports play a key role in the international transport chain and without them the process of production, trade and consumption will not be completed. Therefore, governments try to reduce the time and cost of trade by designing and implementing policies related to the simplification of trade formalities, and by increasing the competitiveness of ports, provide the basis for facing the challenges in port development. In terms of globalization, ports that do not adapt to these changes in terms of infrastructure and port services will lose their competitiveness in terms of throughput capacity [2].

Ports as the basis of maritime trade have changed a lot in recent decades, but in line with these changes, the Ports and Maritime Organization, as the main custodian of port and maritime policies, must adapt quickly. This adaptation and process of change, as well as the generations of ports in the country, should lead to good governance in port management. The evolutionary process of port governance shows that a single solution cannot be used for governance reform in all ports of the world, so in this study we try to analyze and evaluate the factors affecting good governance in an organization that is one of the custodians of transportation and is a link between the development of domestic trade and international trade.

2. Theoretical Framework and Literature of Review

One of the main concerns of developing countries is to be on the path of development. The study of the pathology of development programs in Iran proves that one of the most important reasons for failure in the path of development is the lack of a national and indigenous model for governance in accordance with the values of society, the situation of the country, and the ideals and macro national and local goals which be compatible with the cultural and historical issues of Iran [3]. Governance theory seeks to find the characteristics and prerequisites of development and, more than any other factor, emphasizes the evolution of the internal institutions and structures and the formal and informal laws of societies [4]. The quality of governance has always been a central concern for the political philosophers, theorists and practitioners [5].

It must be remembered that the path towards ‘good governance’ must involve a demonstration of the path towards a viable, unified and stable civil order [6]. Today, citizens expect to receive quality services and meet these expectations require new conditions that need new public services at the macro level of society and governance paradigms. Any model must take into account three basic queries: who, what and how it governs. These three points are directly related to the cornerstones of the governance: its structure, its actions and its own elements. The structure refers to the regulatory framework; the actions, to the tools leading to coordination; and the elements, to the agents and flows [7].

In response to the challenge, many scholars and international organizations have come up with a number of concepts, such as meta-governance, sound governance, effective governance and good governance. Among them, the most influential one is ‘‘good governance’’ [8].

So, good governance is both an end and a means . It is a key goal of development, broadly construed, and it is also an instrument for achieving better policymaking and improved economic outcomes” [9].

Now I briefly mention some recent definitions of good governance:

Good governance refers to the public administration process that maximizes public interest. One of its essential features is that it is a kind of collaborative management of public life performed by both the State and the citizens and a new relationship between political State and civil society, as well as the optimum state of the two[8].

Good governance in the definition of the World Bank is the capacity of management and institutional reforms conducted by state policy that improve coordination and delivery of effective public services, accountability of political actors and individual citizens in the driving of development policies[10].

World Bank broadened the scope in to more aspects and defines Good Governance as: Good Governance consists of traditions and institutions by which authority in a country is exercised. This includes the process by which governments are selected, monitored and replaced; the capacity of the government to effectively formulate and implements sound policies; and the respect of citizens and the state for the institutions that govern economic social interactions among them[11].

Good governance is defined by rule of law, the existence of effective state institutions, transparency and accountability in the management of public affairs, respect for human rights, and the meaningful participation of all citizens, particularly women, in political processes and decisions affecting their lives [12].

Good governance allows reducing the corruption. It promotes gender equality, has a positive impact on sustainable development, allows citizens to enjoy personal freedoms, and delivers tools for combating poverty, privation, fear and violence [13].

In contemporary usage, the concept of good governance has two main meanings. The first and more limited meaning is associated with the World Bank which interprets it in primarily administrative and managerial terms. The second meaning, associated with Western governments, is more political [5]. Since the 1990s, port governance has attracted much attention from the academic, the port authorities, as well as the policy and decision makers operating in the maritime sector, and port governance itself has gradually became an important academic and practical concept in the port field. Although a lot of studies have been published on the topic of port governance, there exists no consensus on the definition of port governance because of the complexity and vagueness of the scope of governance, which states that “governance is the adoption and enforcement of rules governing conduct and property rights [14].

The research in question has shed much light on the new modes of governance, the distribution of the various functions of ports and is now attempting to explain the complex link between performance and governance [15].

The evolution in governance structures of other countries indicate that there is no simple "one size fits all" approach that can be applied to port reform. Some governments around the world view privatization and competition as a solution to attaining port efficiency.

Good ports has different interpretations. For example, privatization in the United Kingdom did not lead to or improve port efficiency; rather it has led to heavy reliance on subsidization in the maritime sector. On the contrary, in China and Korea, it resulted in more efficient ports. As a result of privatization, more transparent governance has been achieved by Korea. Companies that adhere to Companies Act 71 of 2008 and the King Code of Corporate governance are considered to have good governance. The King Code outlines elements for good governance such as transparency, independence, responsibility, discipline, social responsibility and fairness [16]. Figure 1 shows the main actors in governing the port [17].

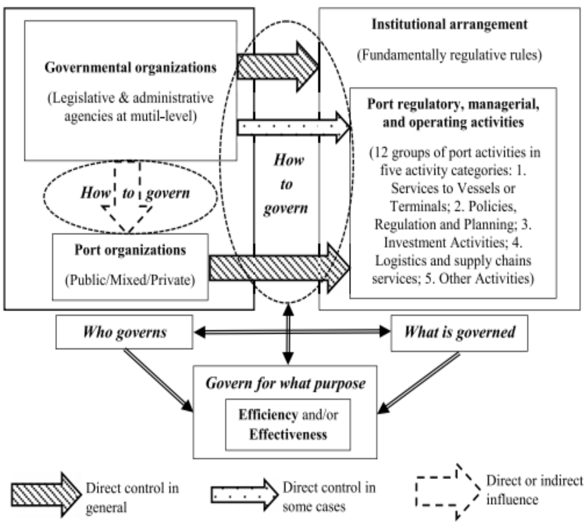


Figure 1. The relationships between the four basic questions of port governance.

Good governance does not form on its own, and various causes and factors play a role in its formation. This model is not limited to one sector or level, but is a pervasive thing that needs to exist in all sectors of a society and its realization requires coordination and readiness of all sectors [18].

Therefore, before presenting and explaining the indicators of good governance and measuring it, it is necessary to determine its level for assessing good governance.

There are four areas or zones where the concept is particularly relevant:

1. Governance in 'global space', or global governance, deals with issues outside the purview of individual governments.

2. Governance in 'national space', i.e. within a country: this is sometimes understood as the exclusive preserve of government, of which there may be several levels: national, provincial or state, indigenous, urban or local. However, governance is concerned with how other actors, such as civil society organizations, may play a role in taking decisions on matters of public concern

3.Organizational governance (governance in 'organization space'): this comprises the activities of organizations that are usually accountable to a board of directors. Some will be privately owned and operated, e.g. business corporations. Others may be publicly owned, e.g. hospitals, schools, government corporations, etc.

4.Community governance (governance in 'community space'): this includes activities at a local level where the organizing body may not assume a legal form and where there may not be a formally constituted governing board [19].

Therefore, in this study, the study of good governance at the organization level in one of the agencies active in the transportation sector is considered, which researchers have paid less attention to it.

Since today's society is an "organizational society", one of the main pillars of achieving good governance is definitely the governing organizations in that society.

Indicators are a good mechanism for introducing and measuring a phenomenon. In this regard, various individuals and institutions introduced indicators of good governance in order to be able to define and identify it, and thus, while identifying good governance, using indicators to measure and assess it in different societies. Considering that there was no pre-determined framework for presenting the components of good governance in the country's ports to study and find the key factors or indicators affecting good governance; therefore, first, through a comprehensive study of previous research records, during library studies of sources such as books, articles and theses, and various publications of domestic and international institutions that were done in order to prepare and compile research literature, we achieved a relatively comprehensive knowledge about good governance, then, by analyzing the content of the most referenced writings and opinions of professors and experts in the field of good governance, the main concepts and characteristics of this approach were identified, which we will use them to explain the components of good governance as follow:

1. Rule of law: The rule of law means that all citizens, especially managers and rulers, obey the law. In this way, all government actions should be within the framework of the law and rulers should be responsible for their actions [20] and knowing how laws are real in a society and to what extent can be enforced [21].

2.Responsibility: In good governance, organizations and institutions must serve the stakeholders and be responsible for the tasks assigned to them [22].

3.Transparency: The free flow of information exchange indicates transparency. Processes, institutions and information are available to citizens who want access and sufficient information is provided to them [23].

4. Participation: The concept of participation refers to the freedom of expression and diversity of views and the organization of a civil society [24].

5.Effectiveness: Processes and institutions produce results that meet needs while making the best use of resources [25].

6. Efficiency: the best use of resources should always be made [25].

7. Responsiveness & Accountability: Who is accountable and to whom varies according to the type of decisions and activities of organizations and individuals. In general, each organization is accountable to those who are affected by its activities. The important point here is that accountability can only be achieved through the exercise of transparency and the rule of law [22].

8. Strategic vision: Leaders and the public have a broad and long-term perspective on good governance and human development, along with a sense of what is needed for such development. There is also an understanding of the historical, cultural and social complexities in which that perspective is grounded [25].

9. Equal Rights and Equity: All men and women have opportunities to improve or maintain their wellbeing [25].

10. Consensus orientation: Good governance mediates differing interests to reach a broad consensus on what is in the best interest of the group and, where possible, on policies and procedures [25].

11. Promoting Values: This index is obtained by measuring and explaining values and behavioral standards for members of the organization and adhering to these values in practice [26].

12. Defining Outcomes: Having a clear organizational goal is a sign of good governance [27]. Because service recipients are confident that they are receiving high quality services [28].

13. Control of Corruption: capturing perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests [29].

14. Capacity Building: Capacity building includes improving human resources, strengthening policy and financial management, and establishing and promoting partnerships for effective economic growth and equity at the global, regional, national, and local levels [20].

15. Regulatory Quality: the capacity of the government to effectively manage resources and implement sound policies, which include the two indicators of "government effectiveness and quality of laws and regulations"[30]. The more the government can develop and implement the activities of the private sector and provide more impact on the governance of society by formulating and implementing various policies and systems, the higher level of governance will occur [21].

Here are some researches on good governance:

-Monios, J. (2016): this paper describes and discusses the UK port sector, the main ports and cargo types, the governance system and recent developments. Recent changes in national policy are reviewed and potential new developments in governance are considered, reflecting on how the UK case represents some key theoretical considerations regarding infrastructure governance within a modern political system favouring private ownership and operation of the transport sector [31].

-Wilmsmeier, G., & Sanchez R.J. (2017): This paper analyses the evolution of port development and port governance in Chile since the 1990s. Current port development is not only challenged by a volatile and slowed down economic environment, but also by changing industry and sclerotic institutional conditions. Applying the matching framework in combination with the life cycle theory, aims to identify how the institutional structures created by port reform evolved and whether these are suitable to manage current and future devolution and changes in the Chilean port system. The paper describes the gains of technical efficiency in the early years after the reform in a decentralized governance structure and asks whether this governance structure is still congruent in the current environment. Some recent attempts to regain national influence have been inhibited by the institutional setting implemented by port reform. The asymmetries of the institutional capacity local and national level become more evident as the life-cycle of the current concession contracts reaches its end, and the existing institutional structure itself might evolve to be the impediment to change [32].

- Zhang & et al (2018): this paper investigates and presents generalized answers to the two basic questions of port governance, namely who governs and what is governed. There are totally 77 studies selected as the core literature sample according to a five-step approach. The results from literature review show evidences in favor of the important roles played by governmental organizations and port organizations as the main governing bodies of port governance. Furthermore, our analysis shows first, that multilevel governance has become a notable feature of port governance. Second, there are increasing involvements by national or regional levels of government in some countries such as the USA, Brazil, China. Third, port authorities at local level are generally holding the Centre-stage position with further autonomy in managing port operations. Fourth, not-for-profit organizations related to port activities play the role of coordinators in port governance. Finally, different governance regimes with different specific governing actors for different port classifications can be identified for many nations. This study shows that fundamentally institutional arrangements and specific port activities are the two basic categories of what is governed [17].

-Zhang & et al (2019): The review paper investigates and presents generalized answers to the two basic questions of port governance, namely how to govern and for what purpose. The study is based on a total sample of 118 studies on port governance. The results from the analysis of these studies show that port devolution and port re-centralization are the main governance tools at the institutional level. At the strategically level, the main governance tools are port competition, port regionalization, port integration, stakeholder management strategy, and corporate governance. While at the managerial level, the main governance tools are port pricing, port concession, port user/ customer relationship management, monitoring and measuring, regulatory control, port security management, and information and communication technologies [14].

3. Methodology

The main purpose of this study is to design an optimal model for the factors affecting good governance in the Ports and Maritime Organization. Therefore, the present study is applied in terms of the purpose of research. Considering that in this research, library study methods as well as field methods have been used, it can be said that the present research is a descriptive-survey research based on its nature and method, and since in this method to collect data about a one or more attributes in a period of time, the community sampling method is used, it can be called cross-sectional survey research.

Since quantitative research methods such as descriptive-survey, descriptive-analytical and experimental alone cannot achieve the reality of phenomena related to organization and management [33], so to eliminate this shortcoming in this research, Fuzzy logic and fuzzy systems theory were used. Given that our real world is too complex to provide an accurate description and definition; so, an approximate or fuzzy description must be introduced for a research model that be acceptable and analyzable [34].

Thus, the fuzzy analysis method introduces both the type of membership (qualitative differences) and the amount of membership (quantitative differences) simultaneously in a "continuum set" that represents the grading of the qualitative states and the amount of membership. Fuzzy science bridges the gap between quantitative and qualitative approaches, and this bridge is built by fuzzy analysis method [35].

4. Statistical Community and Sampling

The statistical population in this study, in order to collect the required information and validate the components of good governance, includes 22 experts in the Ports and Maritime Organization - it is worth mentioning that when there is homogeneity among members, about 10 to 20 members are recommended [36]. The main criteria and characteristics for selecting experts are at least a master's degree in management (theoretical mastery), experience of research activities, practical experience, willingness and ability to participate in research, accessibility and at least 12 years of work experience. The sampling method used in this study, due to the familiarity of specialists and their large number, was random and purposeful sampling method [37].

This questionnaire was approved by professors and experts in terms of apparent validity and conceptual validity. It is worth mentioning that in qualitative research, gaining validity is also associated with gaining reliability. Danaeifar and Mozaffari state that research audit strategies provide us with reliability and validity, which are: 1. Researcher sensitivity: means the existence of creativity, sensitivity, continuous analysis, proficiency and flexibility of the researcher in the research process; 2. Methodological coherence: means the alignment between the question and the elements of the research method; As a result, the research process is done back and forth with continuous re-reading and analysis; 3. Adequacy of sampling: Instead of referring to different people who may not have the necessary information for the researcher, he refers to experts; Therefore, sampling occurs intentionally and selectively. The reference to experts continues until the researcher achieves theoretical saturation (consensus) and concludes that nothing new will be discovered; 4. Simultaneous data collection and analysis; 5. Theoretical thinking: During the research, ideas come to the researcher's mind that are reaffirmed in the new data and may even lead to the modification of previous data and methods. Therefore, all of these strategies gradually and interactively play a role in creating validity and reliability and thus scientific accuracy [38].

In this study, Fuzzy Cognitive Mapping is used. Fuzzy Cognitive Maps are a combination of tools that take advantage of the features of fuzzy logic and artificial neural networks. We will implement the technique for fuzzy cognitive mapping of 15 research criteria in order to design the causal structure and analyze the factors affecting good governance in the Ports and Maritime Organization.

5. Findings

On the one hand, due to that there is a lot of ambiguity in the analysis of factors affecting good governance in the Ports and Maritime Organization, and on the other hand, because that the cause-and-effect relationship between the components cannot be well identified; therefore, in this section, in order to analyze the data, three methods of content analysis, fuzzy Delphi technique and Fuzzy Cognitive Map have been used and each part of the analysis is discussed according to the research questions.

5-1: Content Analysis

In the first part, in order to analyze the content of the research conducted in the field of good governance, the following question is asked:

1. What are the components of good governance based on the content analysis of the existing literature?

Due to the comprehensive study of the components of good governance in related books and articles and the frequency and repetition of the extracted components, a set of components that were comprehensive and covered other components and also were related to the analysis unit of this research - i.e. organizational level - were provided to the group of experts with the initial consent of professors and experts and in order to reduce subjective judgment to extract the final components of good governance in the Ports and Maritime Organization By evaluating and modifying the components. Table 3 summarizes the various indicators of good governance from the perspective of international institutions and researchers:

Resources	Components
(WGIs [39]) , (AGR [40]) , (WBI [41]) , (UNDP [42]) , (Kaufmann et al [29]) , (UNESCAP [43]) , (UN-HABITAT [44]) , (Elahi [45]) , (CIPFA & OPM [46]) , (EC [47]) , (OECD [48]) , (AsDB [49]) .	Responsiveness &Accountability
(IIAG [50]) , (Juiz et al [51]) , (UNDP [42]) , (UNESCAP [43]) , (AfDB [52]) , (UN-HABITAT [44]) , (Elahi [45]) , (CIPFA & OPM [46]) , (OECD [48]) , (AsDB [49]) .	Transparency
(Juiz et al [51]) , (CIPFA & OPM [46]).	Defining Outcomes
(Juiz et al [51]) , (CIPFA & OPM [46]).	Capacity Building
(OPM & CIPFA [46]) , (WBI [41]), (Juiz et al [51]) , (EC [47]) .	Effectiveness
(Juiz et al [51]) , (CIPFA & OPM [46]).	Promoting Values
(WGIs [39]) , (AGR [40]) , (WBI [41]) , (UNDP [42]) , (Kaufmann et al [29]) .	Rule of law
(WBI [41]) , (Kaufmann et al [29]) .	Regulatory Quality
(WGIs [39]) , (AGR [40]) , (IIAG [50]) , (Juiz et al [51]) , (WBI [41]) , (Kaufmann et al [29]) , (AfDB [52]) ,	Control of Corruption
(UNDP [42]) , (OECD [48]) , (UNESCAP [43]) , (UN-HABITAT [44]) (Elahi [45]) .	Equal Rights and Equity
(WGIs [39]) , (AGR [40]) , (Juiz et al [51]) , (UNDP [42]) , (Kaufmann et al [29]) , (UNESCAP [43]) , (UN-HABITAT [44]) , (Elahi [45]) , (CIPFA & OPM [46]) , (EC [47]) , (OECD [48]).	Efficiency
(UNDP [42]) , (UN-HABITAT [44]).	Consensus orientation
(Juiz et al [51]) , (UNDP [42]) , (UN-HABITAT [44]) , (Elahi [45]) , (OECD [48]) , (AsDB [49]) .	Responsibility
(IIAG [50]) , (Juiz et al [51]) , (UNDP [42]) , (UNESCAP [43]) , (AfDB [52]) , (UN-HABITAT [44]) , (Elahi [45]) , (EC [47]) , (OECD [48]) , (Huther, & Shah [53]) , (AsDB [49]) .	Participation
(Juiz et al [51]) , (OECD [48]) ,(UNDP[42]) ,	Strategic vision

Table ١. Extracted components of good governance

5-2. Fuzzy Delphi Technique

In the second part, fuzzy Delphi technique was used to refine and determine the degree of agreement on the identified indicators. Accordingly, the second research question was presented in the following order and then examined:

What are the main components of good governance in the Ports and Maritime Organization?

In this study, the fuzzy Delphi technique was used due to the agreement of the experts on the indicators that are the basis of decision-making and in the fuzzy space that analyzes the verbal opinions of the experts in more detail and was performed in three rounds. In the first round of the questionnaire, which included the identified components of good governance from the content analysis method, experts were asked to rate their agreement on each component in the form of verbal variables in the questionnaire in a seven-choice range ((Completely insignificant 1, Very insignificant 2, Insignificant 3, Medium 4, Significant 5, Very Important 6, Completely important 7). In this regard, in the survey of experts, according to the law 30-70, the limit of acceptability of the criterion is considered to be around 7. If the diffused value of a triangular fuzzy number is 7 or higher according to experts, it is accepted as an acceptable criterion and otherwise it will not be accepted [54].

Then, after the second and third rounds of fuzzy Delphi, the components whose definite mean was less than 7 were removed. In this study, according to the fuzzy Delphi technique, 15 criteria were approved as the final components of good governance according to table 4 and were used to perform the Fuzzy Cognitive Map.

Table 2.Refined components Good governance

Definitive average	components	Definitive average	components
8.52	Control of Corruption(C9)	7.77	Responsiveness &Accountability (C1)
7.03	Equal Rights and Equity(C10)	7.42	Transparency (C2)
7.09	Efficiency (C11)	7.90	Defining Outcomes (C3)
7.01	Consensus orientation(C12)	7.30	Capacity Building(C4)
7.41	Responsibility (C13)	7.90	Effectiveness (C5)
8.10	Participation (C14)	8.65	Promoting Values(C6)
7.46	Strategic vision (C15)	7.73	Rule of law (C7)
---------------------------------		8.05	Regulatory Quality(C8)

5-3.Fuzzy Cognitive Mapping

Fuzzy cognitive mapping is one of the research techniques in soft operations in the field of problem structuring that can provide a hierarchical picture of the causes and their consequences by extracting the experts' mind map. Fuzzy cognitive mapping is an extended version of cognitive mapping that is used to model the complex chain of causal relationships and shows the power of causal relationships with numbers in the range of 1 and -1 [55]. In fuzzy cognitive mapping models, the accumulated experiences of individuals are integrated with the existing knowledge in the field for which the model has been drawn, and based on them, cause and effect relationships are formed between the constituent factors [56]. In other words, fuzzy cognitive maps are a graphical tool for displaying beliefs and ideas, perceptions and interpretations of a situation based on the knowledge and experience of an individual or group, which are described by two elements of concept and causal relationship between concepts. A node or concept refers to an entity, a state or a feature of a system [57]. In fact, the fuzzy cognitive mapping method is one of the tools of cognitive analysis that as an efficient inferential engine has the ability to qualitatively and quantitatively modeling of complex causal relationships. Fuzzy cognitive maps are a combination of tools that take advantage of the features of fuzzy logic and artificial neural networks. Fuzzy cognitive maps are a combination of tools that take advantage of the features of fuzzy logic and artificial neural networks. Due to the focus of fuzzy cognitive maps on feedback loops, it can be considered as a kind of system dynamics method. Dynamic features and learning capabilities of fuzzy cognitive maps make them an extremely suitable tool for modeling, analysis, decision making, forecasting, etc [58].

In the third section, the following question is asked to examine the cause-and-effect relationships between the factors that make up good governance:

3.What is the structure of causal relationships between the components of good governance in the Ports and Maritime Organization?

In this section, we will implement the technique for fuzzy cognitive mapping of 15 research criteria in order to design the causal structure and analyze the factors affecting good governance in the Ports and Maritime Organization, as shown in Table 4.

In this study, this four-step method has been used to find the results of fuzzy cognitive mapping: Initial Influence Matrix of Success (IIMS); Fuzzified Influence Matrix of Success (FIMS); Strength of Relationships Matrix of Success (SRMS); and Final Matrix of Success (FMs) which are used to perform the fifth step of fuzzy cognitive mapping (FCM).

The executive calculations of the fuzzy cognition map technique were performed using FCMMAPER software in the following steps:

Step 1: Form the initial matrix of success

The initial success matrix is an [n × m] matrix in which n is the number of key success factors and m is the number of people to obtain data. Each element of the matrix (O_{ij}) represents the importance that the individual attaches to the concept. The elements O_{i1}, O_{i2}… O_{im} are vector elements related to the key success factors belonging to the matrix row. In this step, the initial matrix of fuzzy cognition map was provided to 22 experts and the initial matrix was formed directly from the experts' response to the questionnaire (the degree of importance of each factor is based on 7-point Likert scale scoring).

Table3. Formation of the initial success matrix

IM	E1	E2	E3	…	E20	E21	E22
C1	4	۴	۵	…	۴	۴	۵
C2	۳	۳	۶	…	۳	۳	۷
C3	۳	۴	۷	…	۳	۴	۶
…	…	…	…	…	…	…	…
C13	۳	۳	۵	…	۳	۳	۵
C14	۳	۳	۶	…	۳	۳	۶
C15	۳	۴	۶	…	۳	۴	۶

Step 2: Form a Fuzzified Influence Matrix of Success

Numerical vectors V1 are transferred to fuzzy sets in which each element of the fuzzy set confirms the membership of the element Oij of the vector Vi with the vector Vi itself. For this purpose, the maximum value is found in Vi and Xi = 0 is considered for it, i.e.

Equation 1:

$$\text{MAX}\ (O_{iq}) \rightarrow X_i\ (O_{iq}) = ۱ \qquad (1)$$

Then find the minimum value in Vi and Xi=0 is considered for it, i.e.

Equation 2:

$$\text{MIN}\ (O_{iq}) \rightarrow Xi\ (O_{iq}) = ۰ \qquad (2)$$

The ratio of all other elements of the vector Vi is determined in the range of zero and one, in which the degree of membership of the element Oij is in the vector Vi.

Equation 3:

$$x_i(O_{ij}) = \frac{(O_{ij} - MIN(O_{ip}))}{(MAX(O_{ip}) - MIN(O_{ip}))} \qquad (3)$$

At this stage, a higher or lower ceiling value is set. If the numerical vector of Vi of the elements m is related to the concepts of i and O_{ij} and is equal to j = 1, 2, 3, …, then, as elements of m, Vi of the higher and lower ceiling values are as follows:

Equation 4:

$$\forall j=1 \ldots m\ o_{ij}\ (o_{ij} \geq a u) \rightarrow Xi\ (O_{ij}) = 1 \qquad (4)$$
$$\forall j=1 \ldots m\ o_{ij}\ (o_{ij} \geq a u) \rightarrow Xi\ (O_{ij}) = ۰$$

The remaining vector elements are estimated in the range of zero and one. In this paper, according to experts, the number seven is considered as the maximum and the number one is considered as the minimum of the data in the calculations.

In this step, using equation (3), we form the fuzzy success matrix and for fuzzifying according to the above relation, we will subtract each element of the initial matrix from the minimum elements of the initial matrix and divide it by the difference between the maximum and minimum values of the initial matrix and place the fuzzy value of each element in the matrix. Each element in this matrix represents the degree of membership of each agent. The result of the fuzzy matrix is given in Table 5.

Table 4. Fuzzified Influence Matrix of Success

FIMS	E1	E2	E3	…	E20	E21	E22
C1	۰/۵۰	۰/۵۰	۰/۶۷	...	۰/۵۰	۰/۵۰	۰/۶۷
C2	۰/۳۳	۰/۳۳	۰/۸۳	...	۰/۳۳	۰/۳۳	۱/۰۰
C3	۰/۳۳	۰/۵۰	۱/۰۰	...	۰/۳۳	۰/۵۰	۰/۸۳
……	… …	… …	… …	…	… …	… …	… …
C13	۰/۳۳	۰/۳۳	۰/۶۷	...	۰/۳۳	۰/۳۳	۰/۶۷
C14	۰/۳۳	۰/۳۳	۰/۸۳	...	۰/۳۳	۰/۳۳	۰/۸۳
C15	۰/۳۳	۰/۵۰	۰/۸۳	...	۰/۳۳	۰/۵۰	۰/۸۳

Step 3: Form a Strength of Relationships Matrix of Success

The Strength of Relationships Matrix of Success is a [n × n] matrix in which each element of the matrix represents the relationship between factor i and factor j. It can also accept values in the range [1 and -1]. Each key success factor is represented as a numerical vector S_{ij} containing n elements for each concept that shown in the map. There are three possible relationships in S_{ij} between concepts i and j. So that $S_{ij}>0$ indicates direct (positive) causality, $S_{ij}<0$ indicates inverse (negative) causality and $S_{ij}=0$ indicates no relationship between the concepts of i and j. The closeness of the relationship between the two vectors V1 and V_2 indicates the strength of the relationship between the variables in relation to these two vectors, which is shown by the element S12 and is presented in the Strength of Relationships Matrix of Success.

If d_j is the distance between elements j of vectors V_1 and V_2 as follows:

Equation 5:

$$d_j = \left| X_1(V_j) - X_2(V_j) \right| \quad (5)$$

And AD is the mean distance between vectors V_1 and V_2:

Equation 6:

$$AD = \frac{\sum_{j=1}^{m} |d_j|}{m} \quad (6)$$

The closeness or similarity of S between two vectors is shown according to this equation (S = 1 confirms complete similarity and S = 0 indicates the maximum degree of dissimilarity):

Equation 7:

$$\mathbf{S} = L - AD \quad (7)$$

In this step, equations (5), (6) and (7) are used to calculate this matrix. This matrix represents the strength of the relationship between the two factors. Different calculations are needed for vectors that are directly related and those that are inversely related.

Table 5. Strength of Relationships Matrix of Success

SRMS	C1	C2	C3	…..	C13	C14	C15
C1	۰/۰۰	۰/۱۱	۰/۵۲	.....	۰/۰۸	۰/۱۰	۰/۴۸
C2	۰/۱۱	۰/۰۰	۰/۱۳	.....	۰/۰۸	۰/۰۵	۰/۰۸
C3	۰/۱۲	۰/۱۳	۰/۰۰	.....	۰/۱۳	۰/۰۸	۰/۰۹
…..	.....	.....	.....	.....	.....	.....	.....
C13	۰/۰۸	۰/۰۸	۰/۱۳	.....	۰/۰۰	۰/۰۶	۰/۰۵
C14	۰/۱۰	۰/۰۵	۰/۰۸	.....	۰/۰۶	۰/۰۰	۰/۰۵
C15	۰/۰۹	۰/۰۸	۰/۰۹	.....	۰/۰۵	۰/۰۵	۰/۰۰

Step 4: Form the Final Matrix of Success

To analyze the data and convert the Strength of Relationships Matrix of Success to the Final Matrix of Success requires an expert opinion that identifies only those fuzzy elements that represent the causal relationships between the key factors of success. In this study, a focus group consisting of a number of experts was formed who expressed their views on the relationship between factors and identified factors that have no relationship with each other.

Table 6. Final Proximity Matrix

FM	C1	C2	C3	…	C13	C14	C15
C1	۰/۰۰	۰/۱۱	-۰/۵۲	...	۰/۰۸	۰/۱۰	-۰/۴۸
C2	۰/۱۱	۰/۰۰	۰/۱۳	...	۰/۰۸	۰/۰۵	۰/۰۸
C3	۰/۱۲	۰/۱۳	۰/۰۰	...	۰/۱۳	۰/۰۸	۰/۰۹
…..	.....	.....	.....	...	.....	.....	.....
C13	۰/۰۸	۰/۰۸	۰/۱۳	...	۰/۰۰	۰/۰۶	۰/۰۵
C14	۰/۱۰	۰/۰۵	۰/۰۸	...	۰/۰۶	۰/۰۰	۰/۰۵
C15	۰/۰۹	۰/۰۸	۰/۰۹	...	۰/۰۵	۰/۰۵	۰/۰۰

Step 5: Graphical representation of fuzzy cognitive map (FCM)

At this stage, a purposeful fuzzy cognitive map is drawn to map the key success factors. In the final representation, each arrow of factors j and i has a symbolic weight that indicates the strength of the causal relationship between the factors and the value in the success matrices in the cell that presented in row i and column j [59]. Based on the final proximity matrix, a good governance graph is obtained according to the following diagram. This diagram shows the relationship between the factors along with their weight. As can be seen in the figure, there are 15 factors as criteria for good governance that are related to weights. According to the causal image, the degree of impact, effectiveness and degree of centrality of the concepts can be shown as the following image. The centrality of the nodes is defined based on the sum of the impact and effectiveness of the concepts (nodes). Impact is the sum of the absolute values of the output relations of the node, and effectiveness is the sum of the absolute values of the input relations of the node. To draw a fuzzy cognitive map, we use the output of FCMapper software as input to Gefi software. The following figure shows the fuzzy cognitive map that shows the causal relationships between the factors.

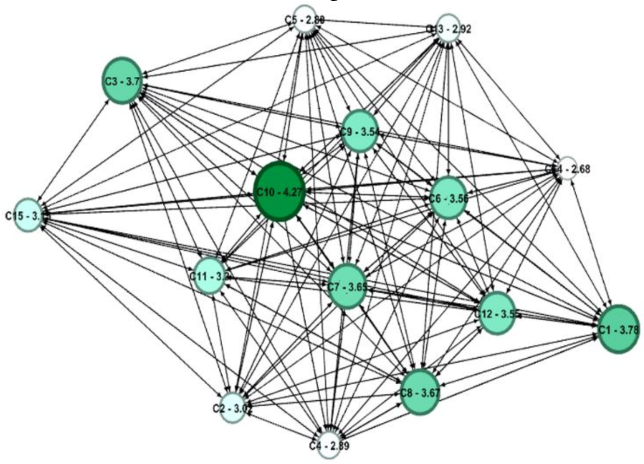


Figure 2: Fuzzy cognitive mapping of good governance (degree of centrality)

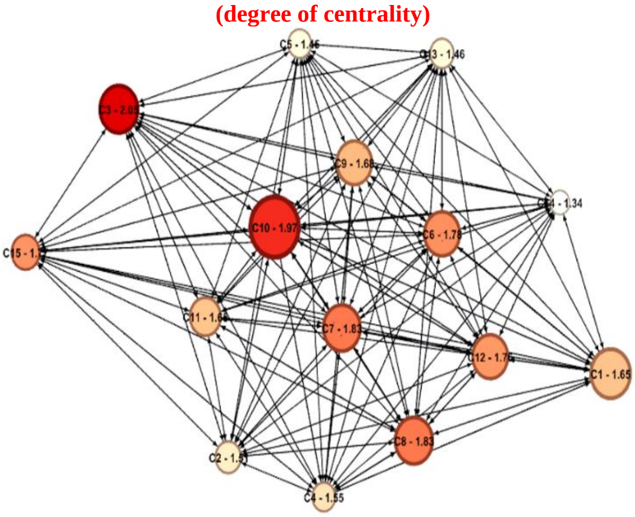


Figure 3: Fuzzy cognitive mapping (input degree)

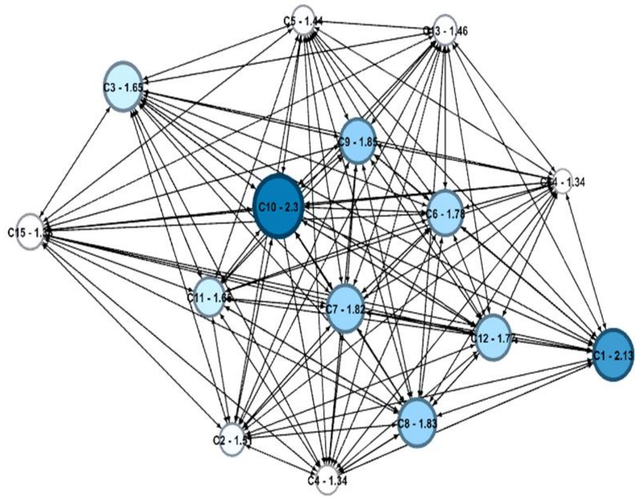


Figure 4: Fuzzy cognitive mapping (output degree)

According to 15 main criteria involved in cognitive mapping, 206 relationships between factors were extracted. The degree of input (id) is the degree of influence of the factors and the degree of output (od) represents the effects applied by a concept, in other words, it shows the degree of influence of the factors and the degree of centrality is the sum of the previous two factors. The type of elements is determined based on their input and output degrees. The input degree is obtained from the sum of the absolute value columns of the values of an element in the proximity matrix and represents the cumulative power of the influential elements in the element in question. The output degree of an element is obtained from the line sum of the values of an element in the proximity matrix and shows the cumulative power of that element [55]. The degree of centrality is the sum of the previous two factors. Any factor that has a higher degree of centrality, in fact, has either higher (od) or higher (id) than other factors, and in both cases, this factor is considered an important factor in the system and should be considered. In the above graphs, the color scheme from dark to light

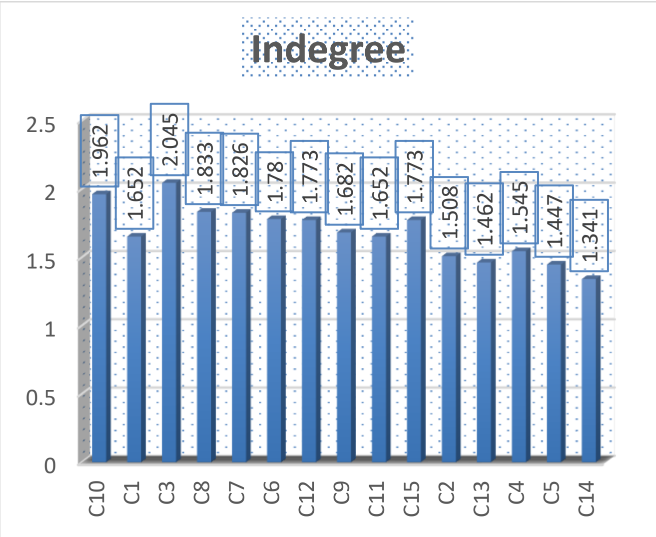
GG	Number of entry paths per node	Number of output paths per node	id	od	Cen
C10	۱۲	۱۴	۱/۹۶۲	۲/۲۹۵	۴/۲۵۸
C1	۱۴	۱۲	۱/۶۵۲	۲/۱۲۹	۳/۷۸۰
C3	۱۴	۱۴	۲/۰۴۵	۱/۶۵۲	۳/۶۹۷
C8	۱۴	۱۴	۱/۸۳۳	۱/۸۳۳	۳/۶۶۷
C7	۱۴	۱۴	۱/۸۲۶	۱/۸۲۶	۳/۶۵۲
C6	۱۴	۱۴	۱/۷۸۰	۱/۷۸۰	۳/۵۶۱
C12	۱۴	۱۴	۱/۷۷۳	۱/۷۷۳	۳/۵۴۵
C9	۱۳	۱۴	۱/۶۸۲	۱/۸۵۶	۳/۵۳۸
C11	۱۴	۱۴	۱/۶۵۲	۱/۶۵۲	۳/۳۰۳
C15	۱۴	۱۴	۱/۷۷۳	۱/۳۷۹	۳/۱۵۲
C2	۱۴	۱۴	۱/۵۰۸	۱/۵۰۸	۳/۰۱۵
C13	۱۴	۱۴	۱/۴۶۲	۱/۴۶۲	۲/۹۲۴
C4	۱۳	۱۲	۱/۵۴۵	۱/۳۴۸	۲/۸۹۴
C5	۱۴	۱۴	۱/۴۴۷	۱/۴۴۷	۲/۸۹۴
C14	۱۴	۱۴	۱/۳۴۱	۱/۳۴۱	۲/۶۸۲

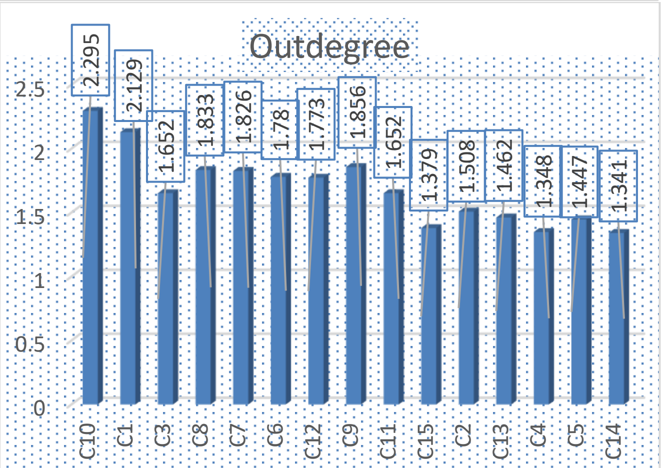
indicates the degree of centrality with high to low weights. For example, the Equal Rights and Equity node (C10) has the highest weight and the lowest weight related to participation (C14).

As shown in the table above, in this study, the factors of Equal rights and Equity (C10), Responsiveness and Accountability (C1) and Consensus Orientation (C3) have the highest degree of centrality, respectively, which indicates the importance of the above variables among the variables of good governance in the Ports and Maritime Organization.

Table 7. Output information of fuzzy cognitive mapping model

In the following diagrams, in fact, in-degree is the degree of influence of factors and out-degree is the applied effects and centrality shows the degree of centrality of good governance.





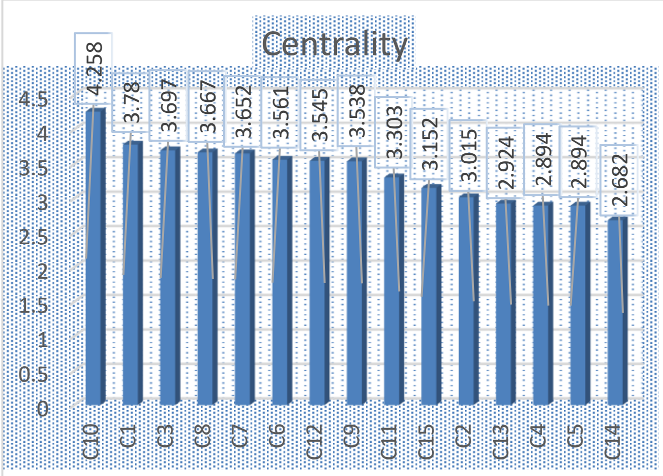


Figure ۵. Bar charts of In-degree, Out-degree and Centrality

6. Conclusion:

The Ports and Maritime Organization, as one of the governmental organizations (for-profit trade) in charge of the transportation sector, always plays a strategic role in the development of domestic and international trade. Due to the large volume of exports and imports of goods, the development of the country's ports as communication gateways is necessary because ports are among the factors accelerating the development of national and regional economy and one of the main links in maritime transport and entry and exit points of goods. Due to the growth of global trade, port traffic has increased, ships become larger, the composition of the goods that are transported has become more diverse and simultaneously with the construction of larger ships, modes of transportation have developed and the time of arrival of ships in ports has become significantly more important. Therefore, ports that do not adapt to these changes in terms of infrastructure and port services will lose their competitiveness in cargo handling throughput. On the other hand, providing services in ports is a function of the management style in them, which itself reflects the quality of governance, but in response to how the quality of governance is measured and what factors are affected, different levels of governance are considered (twelve levels) and among the various levels, the most comprehensive are good governance. Good governance has indicators such as transparency, accountability, corruption control, participation rate, rule of law, etc. In addition to measuring quality, these indicators are like a clear roadmap that facilitates the achievement to the goals. Therefore, in order to identify and extract the effective components based on previous studies, the final components were extracted with the opinion of experts using fuzzy Delphi technique, and then the causal structure between the components was plotted through a fuzzy cognition map with the help of a graph. In this study, based on the capabilities of the fuzzy cognition map technique in modeling and decision making, the effective components in good governance were analyzed and based on the results of the data obtained from the causal structure, it was determined that the components of " Equal Rights and Equity "," Responsiveness & Accountability "," Consensus orientation ", "Quality of Regulations" and "Rule of Law" have the greatest impact on good governance and should be given special attention in decisions by those in charge. Therefore, in order to implement good governance, decision makers must first pay special attention to introducing facilities and opportunities for everyone (both organizational and non-organizational) and always plan to create equality to hold the organization accountable to stakeholders in various ways that this will certainly result in the provision of quality services and by designing a fair and impartial legal framework for more active presence and development of the private sector, these services can be developed and implemented to be provided to stakeholders.

7. References:

1- Bavarsad, P., Jamshidi, S., & Jamshidi, Z., (2016), Application of Fuzzy Dematel Model to identify and analyze the relationship between factors affecting port privatization in Iran, Journal of oceanography, Volume 7, Number 25, spring, pp.23-31 (In Persian).

2- Saraei, K., (2006), Membership of Iran at the WTO and its impact on Iranian port, 14th Conference of Marine Organs, Transit and Tariff Department, PMO, 9-11 may, Mahmoudabad (In Persian).

3- Salimi, J., Maknoon. R., (2018), Qualitative Meta-analysis of Scientific Researches Concerning the Issue of Governance in Iran, Journal of Public Administration (JPA),Volume 10, Issue 1, P.1-30 (In Persian).

4- Amiri, A., Rezghi Rostami A., Gelard, p., & Salehi Sadaghiani, j., (2020), A Model for Good Governance in the Defense Sector of the Islamic Republic of Iran and the Need to Use It, *Quarterly Resource management in Police,* Volume:8, Issue: 30, p. 181 – 214 (In Persian).

5- Shankar Nag, N., (2018), Government, Governance and Good Governance, Indian Journal of Public Administration, Dayal Singh Evening College, University of Delhi, New Delhi, India,64(1), p.122–130.

6- Ahluwalia, P., & Miller, T., (2020), The continuing importance of good governance, Social Identities, Social Identities , Journal for the Study of Race, Nation and Culture, Volume 26, Issue 1, 26(1), p.1-2.

7- González, L. F., Sánchez, R. J., & Garcia, A., (2016), The adaptation process in port governance: the case of the Latin countries in South America and Europe. Journal of Shipping and Trade, 1(14), p.1-20.

8- Keping, Y., (2018), Governance and Good Governance: A New Framework for Political Analysis, Fudan Journal of the Humanities and Social Sciences, volume 11, p.1-8.

9- Danuta, G.D., Zbucki, Ł., Agnieszka, K., (2020), Good governance in strategic planning of local development in rural and urban-rural gminas of the eastern peripheral voivodeships of Poland, Bulletin of Geography, Socio–Economic Series, No.49.P.101-112.

10- Mira, R., & Hammadache, A., (2018), Good Governance and Economic Growth: A Contribution to the Institutional Debate about State Failure in Middle East and North Africa, Université Paris 13, CEPN Laboratory. France; IFC, Renmin University (China), p.107-120.

11- Baha, H. (2016). Good Governance and Human Development: The case of Afghanistan, Submitted in fulfilment of the partial requirements for the degree: Master of Public Policy and Good Governance, Public Economics, Law and Politics, Address: 29549 BadBevensen, Rathaus Straße 9, Thesis.

12- Wani H. A., Suwirta, A. (2015). Changing Dynamics of Good Governance in Africa. International Journal for Educational Studies, 7(2) February, by Minda Masagi Press Bandung and UMP Purwokerto, Indonesia ISSN 1979-7877, p.189-202. Website: www.educare-ijes.com.

13- Poniatowicz, M., Dziemianowicz, R., Kargol-Wasiluk, A., (2020), Good Governance and Institutional Quality of Public Sector: Theoretical and Empirical Implications, European Research Studies Journal XXIII, Issue 2, p.529-556.

14- Zhang, Q., Zheng, S., Geerlings, H., El Makhloufi, A., (2019), Port governance revisited How to govern and for what purpose? Journal of Transport Policy, Volume77, May, p.46–57.

15- Debrie, J., (2011), Different tiers of government in port governance: some general remarks on the institutional geography of ports in Europe and Canada, 12th World Conference on Transport Research, Jul 2010, Lisbonne, Portugal. p.1-16.

16- Mokone, T., (2016), The impact of governance structure on the port performance: a case of Durban Port, World Maritime University Dissertations,533, World Maritime University, Malmo, Sweden, p.1-69.

17- Zhang, Q., Geerlings, H., El Makhloufi, A., Chen, S., (2018), who governs and what is governed in port governance: A review study. Journal of Transport Policy,Volume 64, May, p.51–60.

18- Dowleh, f., Sayfollahi, S., Zanjani, H., (2019), Study the Context and Barriers to the Formation of Good Governance in Contemporary Iran, Quarterly professional Journal of social sciences, Volume 13, Issue 2, Serial Number 45,spring, p.123-154 (In Persian).

19- Graham, J., Amos, B., & Tim, P., (2003), Principles for Good Governance in the 21 Century, The Institute On Governance (IOG), Policy Brief No. 15, Institute on Governance, Ottawa, Canada. Retrieved from: www.io g.ca.

20- Emami, M., & shakeri, H., (2016), Good governance and The constitution of the Islamic Republic of Iran. Journal of Comparative Law Biquarterly, Volume 1, Issue 2, summer and autumn, p. 25-57 (In Persian).

21- Arab yarmohammadi, J., & Esmaeili Khoshmardan, A., (2019), Indicators of good governance and assessment of the situation in Iran, Scientific Supervisor: Yekta Ashrafi, Economic Affairs Research Institute, report identifier: 9901020083, P.1-38 (In Persian).

22- Araei, V., Ghasemi, A., & Moeininfar, Y. (2018).Policy Recommendations about Barriers of Good Governance in Public Affairs (Case Study: Governorate and Municipality of Minoodasht), Journal Strategic Studies of public policy, Volume, winter, p.113-133 (In Persian).

23- Zarghani, S. H., Ahmadi, E., (2019), Good Governance in Local States: Decentralization Approach, Journal State Studies quarterly, Volume 5, Issue 19, Autumn, pp.107-138 (In Persian).

24- Heshmatzadeh, M.B., Haji Yousefi, A.M., & Talebi, M.A.(2017), Investigation of Obstacles to realization of Good Governance in Iranian Political Culture, *Journal of "Contemporary Political Investigations"*, Volume 8, Issue 23 - Serial Number 23,Summer, pp.1-24 (In Persian).

25- Jindal, N., (2014), Good Governance: Needs and Challenges, International Journal of Scientific & Engineering Research, Volume 5, Issue 5, May, Jaypee University of Information Technology, p.113-116.

26- Yar Ahmadi, M., Almasifard, M.R., (2017), Investigating the good governance in public organizations (case: Kermanshah province), 1st International Conference on Economic Planning, Sustainable and Balanced Regional Development; Approaches and Applications, Sulaimani Polytechnic University, University of Kurdistan (In Persian).

27- Moghimi, S.M., & Alaei Ardakani, A. (2011). Indicators to Measuring good governance and its role promoting e-government. Journal of Information Technology Management (JITM), Volume 3, Issue 8 - Serial Number 8, pp.171-188 (In Persian).

28- Hamzei, M., Baradaran, M.M., & Hatefi, F., (2013), Good governance in Mashhad Municipality, 5th Urban Planning and Management Conference, 24 & 25 April, Mashhad. (In Persian).

29- Kaufmann, D., Kraay, A., & Mastruzzi, M. (2010), The Worldwide Governance Indicators Methodology and Analytical Issues, The World Bank Development Research Group Macroeconomics and Growth Team, Policy Research Working Paper, p.1-31.

30- Sahraie, A., & Mahmoodinia, A., (2018)., Good governance: The Framework for Analysis of Hashemi's political Economy. Journal of Strategic Studies of public policy, Volume 8, Issue 28,Autumn,P.207-228 (In Persian).

31- Monios, J., (2016), Port Governance in the UK: Planning without policy. Transport Research Institute, Edinburgh Napier University Merchiston Campus, Edinburgh, United Kingdom, 22, p.78-88.

32- Wilmsmeier, G., & Sanchez R.J., (2017), Evolution of national port governance and interport competition in Chile, Research in Transportation Business & Management, 22, p. 171–183.

33- Felinia A., (2020), Designing and explaining the effective model of organizational image processing in the tourism industry of Iran, Thesis to earn a Master of Science Degree, School of Management, Azad University of Chalous Branch (In Persian).

34- Naghade, F., (2013), Fuzzy logic applications in machine learning, In Partial Fulfillment of the Requirement for the degree of Bachelor of Science in Information Technology Engineering, Faculty of Engineering, Payam Noor University of Isfahan-kashan (In Persian).

35- Golshani, A., & Ghaedi, M., (2014), Fuzzy Method in Research: A Bridge between Quantitative and Qualitative Research Methods, journal of Psychological methods and models ,Volume 4, Issue 14, Serial Number 14, winter, p. 45-65 (In Persian).

36- Farnaz Roozban, A., Farhangi, A.A., hosein Damghanian, H., & Rastegar, A., (2019), Presenting and explaining organizational communication management model in the context of social networks, quarterly of Cultural Studies and Communication, Volume 15, Issue 54, spring, p.103-126 (In Persian).

37- Rahmani, A., Vaziri Nezhad, R, Ahmadi Nia, H., & Rezaeian, M., (2020). Methodological Principles and Applications of the Delphi Method: A Narrative Review, JRUMS, 19 (5), p.515-538 (In Persian).

38- Gol Verdi, M., Zareie Matin, H., & Jandaghi, G.R., (2016), Identification of Factors Affecting Succession Management Behavior in Managers: Qualitative Approach, Journal of Research in Human Resources Management, Volume 8, Issue 2 - Serial Number 24, summer, p.183-208 (In Persian).

39- WGIs (The Worldwide Governance Indicators)., (2019), Report on six broad dimensions of governance for over 200 countries and territories over the period 1996-2019, Retrieved from: https://info.worldbank.org/governance/wgi/Home/Documents.

40 - AGR (The Africa Governance Report)., (2019), Promoting African Union Shared Values, Prepared by The African Peer Review Mechanism (APRM) In

Collaboration with the African Governance Architecture (AGA), January.
41- WBI (World Bank Institute)., (2012), Governance data web-interactive inventory of datasets and empirical tools, Washington, dc. Retrieved from: www.worldbank.org/wbi/governance/govdatasets/index.html.
42- UNDP (United Nations Development Programme)., (2011), Towards Human Resilience: Sustaining MDG Progress in an Age of Economic Uncertainty, pp.268-278. Retrieved from: www.undp.org.
43- UNESCAP (United Nations Economic and Social Commission for Asia and the Pacific). (2009).What Is Good Governance?. 1-3, Mr.Yap Kioe Sheng Chief, Poverty Reduction Section UNESCAP, UN Building, Rajdamnern Nok Ave. Bangkok 10200, Thailand.
44- UN-HABITAT (The United Nations Human Settlements Program)., (2006), the urban governance index: a tool of the quality of urban governance, Beirut.
45- Elahi, K. Q., (2005), Economic Inequality and Paretian Welfare Economics: Some Insinuating Questions, BRAC University Dhaka, Bangladesh, FSSE 35, Forum for Social Economics, Volume 35, Issue 1, p.19–36.
46- CIPFA & OPM (The Chartered Institute of Public Finance and Accountancy and Office for Public Management)., (2004), The Good Governance Standard for Public Services. The Independent Commission on Good Governance in Public Services. London. P.1-38.
47- EC (Commission of the European Communities). (2001), European Governance, A White Paper, Brussels, p.8-10.
48- OECD (Organization for Economic Cooperation and Development). (2000). Directorate for Public Governance and Territorial Development. Principal Elements of Good Governance. Retrieved from: https://www.oecd.org.
49- AsDB (The Asian Development Bank)., (1995), Governance: Sound Economic Management. August, pp.3, 4, 8.
50- IIAG (The Ibrahim Index of African Governance of Mo Ibrahim Foundation)., (2019), AGENDAS 2063 & 2030, IS AFRICA ON TRACK? Index Report.
51- Juiz, C., Guerrero, C., & Lera, I., (2014), Implementing Good Governance Principles for the Public Sector in Information Technology Governance Frameworks, *Open Journal of Accounting*, 3, pp.9-27, published Online January, Retrieved from: (http://www.scirp.org/journal/ojacct).
52- AfDB (The African Development Bank)., (2008), Governance Strategic Directions and Action Plan Gap 2008-012, April, p.15.
53- Huther, J., & Shah, A., (2000), Anti-Corruption Policies and Programs: A Framework for Evaluation, Policy Reserch Working Papers, December, p.1-17.Available at SSRN: https://ssrn.com/abstract=632571
54- Samadi Mirkolaei, Ho., Samadi Mirkolaei, Ha., Bastami M., (2017), The Application of Fuzzy Delphi Method and Fuzzy AHP in Verification and Ranking of Effective Indexes on Organizational Entrepreneurship, Journal of Innovation and Entrepreneurship, Spring-Summer, Volume6, Number 11, P. 61-74 (In Persian).
55- Mostafaee, KH., Azar, A., Moghbel Baarze, A., (2019), Identification and Analysis of Operational Risks: A Fuzzy Cognitive Map Approach, Journal of Asset Management and Financing, Volume 6, Issue 4, Serial Number 23, winter, p. 25-57 (In Persian).
56- Talebpoor, A.R., Ahmadi, S.,(2010), intelligent evaluation Intelligent fuzzy cognitive mapping (FCM) , Journal of Management perspective, Volume 30, p.9-28 (In Persian).
57- Nikshapoori, M., Abbasnejad, T., Ahmadi Kahnali, R., (2019), Analysis of Causal Relationships between Green Productivity Indicators with Fuzzy Cognitive Mapping Approach, Journal of Industrial Management Perspective , Volume 8, Issue 4, Winter, Serial Number 32,Winter, P.97-119 (In Persian).
58- Jafari Eskandari, M., Farhang, M., (2016), Designing fuzzy cognitive map model of factors affecting cost-time-quality in oil and gas projects Case study: Refinery of 15 companies of South Pars Gas Complex, scientific Journal of oil and gas exploration & Production, Volume 1394, Issue 125, July, p.30-۳7 (In Persian).
59- Ahmadnezhad, A., Sangari, M.S. Bozorgi. A.A., (2018), Modeling Key Readiness Factors of Hospitals for E-procurement System Using Fuzzy Cognitive Map (Case Study: A Specialty Hospital in Tehran). Journal of payavard salamat, 11 (6), p.660-674 (In Persian).

INTERNATIONAL JOURNAL OF
COASTAL & OFFSHORE ENGINEERING

IJCOE Vol.6/No. 2/Spring 2021 (47-55)

Available online at: www. Ijcoe.org

Integration of geographical information system and Wave Hindcast model - case study: Persian Gulf

Masoud Moradi

Associate Professor, Iranian National Institute of Oceanography and Atmospheric Science; moradi_msd@yahoo.com

ARTICLE INFO

Article History:
Received: 07 Dec. 2020
Accepted: 01 Jun. 2021

Keywords:
Numerical modeling
Data management
Wave atlas
Wind data

ABSTRACT

In this study, a numerical third-generation wave model was performed to generate 10 years (2000-2010) of wave hindcast in the Persian Gulf. The modified wind field data of European Center for Medium Range Weather Forecasts (ECMWF) and bathymetry data were used as the input data to model. In situ measurements and satellite-derived wave height were performed for model calibration, and validation the results. The results show that the overall accuracy is more than 80% over the whole Persian Gulf. Geographical Information System (GIS) was used to handle all datasets through a user-friendly software which provides required tools for data visualization and manipulation. Data management was carried on using the integration of Relational Database Management Systems (RDBMS) and GIS components.

1. Introduction

Persian Gulf is a semi-enclosed marginal sea in a typical arid zone and it connects to the Indian Ocean through the Strait of Hurmuz. The gulf is 990km long and its width ranges from 56 to 340 km. Its total volume is 7000–8400 km3 of seawater [1, 2]. The most area of basin lies upon the continental shelf [3]. The average water depth is 35.0 m, and some locations with depths more than 107m were observed. The depth increases from south toward the northeast. Geopolitically and economically Persian Gulf is one of the most pathways in the world.

Long term data of sea waves are very essential from safety and economic point of view for such projects [4]. The lack of adequate information on the physical and environmental characteristics of sea state will be pretend either in an unsafe structure or with an over-designed structure in this region [5]. In the study area, there is no long-term wave datasets which are essential for design of coastal structures. In practice, the modeled hindcast wave data is usually used for such purposes. Since 1980s, several professional numerical models have been developed for weather prediction and sea wave modeling by international agencies (i.e., U.S. Navy Fleet Numerical Meteorology and Oceanography Center, U.S. National Center for Environmental Prediction, U.S. Navy Operational Global Atmospheric Prediction and European Center for Medium-Range Weather Forecasts). Nowadays, sophisticated wave models are run at many meteorological centers in the world, and also dedicated long term hind-casts have been performed [6, 7, 8, 9, 10]. Although Met-Ocean datasets are freely available in global scales by these agencies, spatial and temporal high resolution regional datasets and numerical models are required for coastal engineering and environmental purposes [11].

However, to get a reliable understanding of the wave climate in the Persian Gulf, few wave hindcast study have been performed locally or over the whole gulf. EL-GINDY and HEGAZI [3] provided a hydrographic atlas for the Persian Gulf and Oman Sea. However, they focused on the tidal and density driven currents. Also, another oceanographic atlas has been developed by AL-YAMANI et al. [12], which provides valuable oceanic datasets around the Kuwaiti territorial waters. This atlas does not cover the whole Persian Gulf, and also does not cover the complete hydrodynamic characteristics of the Kuwaiti territorial waters. A comprehensive met-ocean model of the Persian Gulf (PERGOS) has been developed by DHI Water and Environment together with Ocean Weather Inc for the whole Persian Gulf. The wind and wave hindcast datasets were modeled in PERGOS in basin-wide grids of spacing 0.0625 degrees in latitude and longitude (7 km) nested within coarser grid systems. Two-dimensional surge, tide, and currents have been simulated in this atlas using DHI's MIKE 21 using a mesh resolution less than 7 km. The datasets available for a period of 20 years from 1983 [www.dhigroup.dk]. PERGOS is just commercially available and cannot be distributed freely. In addition, it does not available through a user-friendly digital atlas, and users have to purchase the DHI's commercial softwares to use the results of PERGOS.

Rakha et al. [5] have developed a hydrodynamic atlas for the Persian Gulf. They have used the WAM and RMA-10 models for their simulation. It is a good challenge at the end of this paper to compare the results of Rakha et al. [5] with our results, because different models and basic data have been implemented. Other centers have also generated similar data for the Persian Gulf. However, these datasets are available in coarse grids that do not provide adequate and reliable data for coastal engineering application [13, 14, 8, 5].

Such as of many other oceanic phenomena, knowledge of wave climate and its application in marine engineering needs data and information. At the technical level, integrated management of the ocean and seas relies on two basic tools: Modeling & Data [4]. Modeling acts as a tool so that the environment modeling-decision making relationship is developed as a bridge between scientific research and policy analysis. However, availability of raw and modeled data is not a sufficient condition to produce the required information about the oceans and seas. It is the utility or usefulness of data that contributes to production of information. Transfer of wave modeled data into information involves several activities such as spectral, Statistical, spatial and temporal analysis [15]. Each of these activities contributes to retrieval of the required information from raw data. Spatial nature, large volume and organization of wave modeled data and information are the most important aspects in the sea wave data management and visualization that directly support the good decision making for coastal engineering application of these datasets. However, through the use of Geographical Information System (GIS) and the associated software; these data can be managed, compiled, and processed. Integration of GIS with wave hindcast datasets accomplish a number of significant functions such as: manipulation, modifying, data analysis and visualization [16]. GIS improves the ability to incorporate spatial details beyond the existing capability of numerical models [17].

This paper describes the methodology and general approaches toward the wave hindcast in the Persian Gulf. The first attempt began by deploying some wave measurement stations, and other data sources such as satellite data and results of the other regional and large-scale numerical models. In this study a third-generation wind driven wave model is used to model the wind waves. A 10-year database is generated from 1st January, 2000 till 31st December, 2010. Modeled data were tuned using measured data and thus the data provided by the models can be used with confidence. In this study, all generated data are converted as a geographic database schema, and we aim to generate an interactive hydrodynamic atlas. Here, we aim to present a methodology for data management and application of the modeled sea wave datasets using GIS.

2. Data and methods

Equations start from the far left of the row. They are numbered consecutively. The equation numbers must be bracketed and placed opposite to the equation on the far right of the line.

The bathymetric data, satellite data, wind fields and the results of wave hindcast data have been used in this study [Table 1]. The bathymetry data were compiled from the combination of Mike C-Map [18] and hydrographic charts after a QC check [Figure 1a]. Wind data were gathered from operational ECMWF with a reasonable spatial resolution required for this study. In situ measurements obtained from weather synoptic stations and buoys, and satellite-derived wave data were used for data validation after a QC check. Details of these datasets have been shown in Figure 1b and Table 2.

In this study, Mike 21 spectral wave model SW, a third-generation spectral wind-wave model based on unstructured meshes [18], has been used. This model uses the wind fields for simulation of wind generated waves and swells in offshore and coastal areas. The wind-wave interaction (generation), wave-wave interaction (quadruplet), dissipation and bottom friction physical processes are included in the model. The model was setup for the entire Persian Gulf with a grid spacing of 0.125 degree. The output of model was utilized in 16 directions, 25 frequency bands, and a time step of 900 seconds.

3. Results

The quality and accuracy of wind data directly influence the results of any numerical wave hindcast models [19, 11]. For example, in an open ocean area, wave height approximately corresponds with the wind speed by a square factor [20]. Therefore, the accuracy of wind data is the most important key in the wave hindcast study. ECMWF wind field showed relatively good agreement with in situ measurements in the offshore regions, and with satellite measurements. In contrast, wind speeds at coastal areas were underestimated due to the rectangular land-sea mask and corresponding surface roughness along coastlines of the Persian Gulf [Figure 2a, b]. The exceedance diagrams of some coastal selected points from ECMWF wind data showed underestimate shift in comparison with in situ and satellite measurements [Figure 2c]. Here, wind field data were optimized by transferring data from offshore grids to the nearshore grids without any interpolation or extrapolation, and as well as by performing an increasing factor [20]. The results of this procedure revealed a good correlation of wind field data with in situ and satellite measurements [Figure 2d].

Table 1. Specification of datasets used in this study

Group	Database	Provider	Resolution	Limitation	Implementation Status	Ref
Bathymetric Data	Admiralty maps	UKHO	Sc: 1/150.000 – 1/50.000	No full coverage	Complementary XYZ data*	Fig 1
	Mike C-Map	DHI	Sc: 1/150.000 (C level)	No more high resolution	reference for bathymetry data	
	NCC Maps	NCC	Sc: 1/25000, 1/100.000	No full coverage	Complementary XYZ data	
	NGC Maps	NGC	Sc: 1/25000 – 1/100.000	No full coverage	Complementary XYZ data	
Wind Fields	ECMWF	ECMWF	S: 0.5 X 0.5, T: 3 h	Needs modification at coastal area	reference for wind field data	
	NCEP/NCAR	NCEP	S: 2.5 X 2.5, T: 6 h	Spatial resolution is coarse	Used for model validation	
	UKMO	OCEANOR	S: 1.25X0.833, T: 6 h	No full temporal coverage	Used for model validation	
In situ data	Synoptic Stations	IRIMO	T: 3 h	No continuous recorded, needs QC	Used for model validation	Fig 1, Table 2
	Buoy data	IRIMO, PSO, NIOC	Not unique for all stations	No continuous recorded, needs QC	Used for model validation	
Satellite data	Sat. altimetry+	AVISO / NASA	T: 10 days	Temporal resolution is too coarse	Used for model validation	Fig 1
	Quick Scat	NASA	S: 0.25X0.25, T: 4 days	Temporal resolution is too coarse	Used for model validation	
Wave modeled data	Persian Gulf Hydrodynamic Atlas	Rakha et al. (2007)	S: 0.1 X 0.1 T: 300 sec	no source data available	Results used for comparison	
	PERGOS	DHI	S: 0.0625, T: 6 h	Commercial license only	Demo version used	

+: Topex/Poseidon and Jason-1 along track Wave height and Wind Speed girded data

Avb: Availability (in the final Atlas database)

Ref: Reference (in this paper)

DHI: DHI water & Environment

NCC: National Cartography Center of Iran

NGC: National Geographic Center of Iran

PSO: Ports and Shipping Organization of Iran

NIOC: National Iranian Oil Company

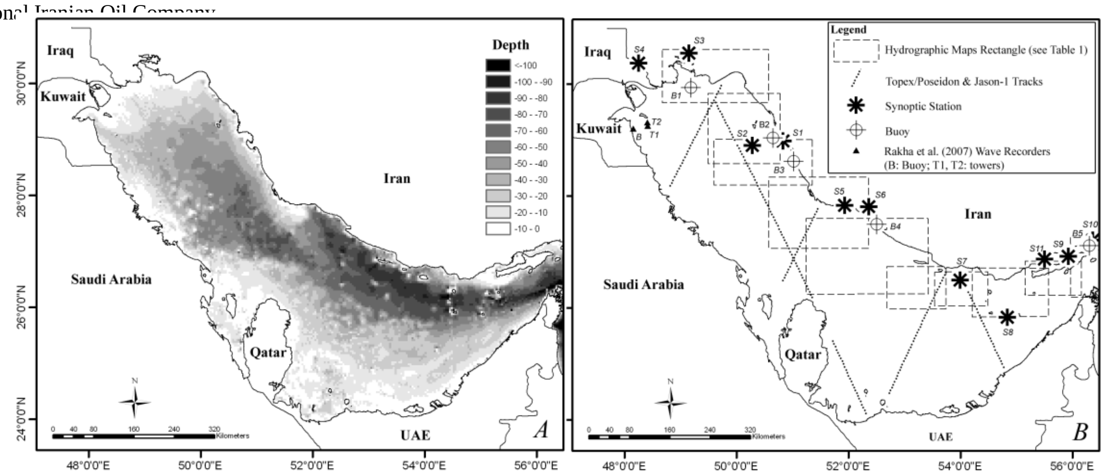


Figure 1. (a): Bathymetry map, (b): Basic datasets used in this study. Refer to Table 1 & 2.

Table 2. Details of the in-situ measurements used in this study

Category	Label in fig 1	Period	Lon	Lat	Elev./Depth	Measured Parameters
Synoptic Station	S1	2000-2010	50.83	28.98	+19.6	Wind Speed Wind Direction
	S2	2000-2010	50.82	28.90	+8.4	
	S3	2000-2010	49.15	30.55	+6.2	
	S4	2000-2005	48.25	30.37	+6.0	
	S5	2000-2006	51.93	27.83	+4.0	
	S6	2000-2010	52.36	27.81	+6.5	
	S7	2000-2010	53.99	26.50	+30	
	S8	2000-2008	54.83	25.83	+6.0	
	S9	2004-2006	55.92	26.93	+6.0	
	S10	2000-2008	56.36	27.21	+10.0	
	S11	2000-2010	55.30	26.76	+5.2	
Buoys	B1	2010	49.18	29.93	-17.0	Hs, Tz, Tp
	B2	2000-2008	50.65	29.04	-15.0	Hs, MWD
	B3	2000-2005	50.70	28.91	-27	Hs, Tp, Tz, MWD*, T01, T02
	B4	2000-2006	52.50	27.59	-7.5	Hs, MWD*, Tz, Tp
	B5	2000	56.29	27.11	-5.2	Hs, Tz, Tp
Rakha et al. (2007) observations	B	1994-2006	-	-	-	Wave height and period (time series graph available)
	T1	1994-2006	-	-	-	
	T2	1994-2006	-	-	-	

*MWD: Mean Wave Direction

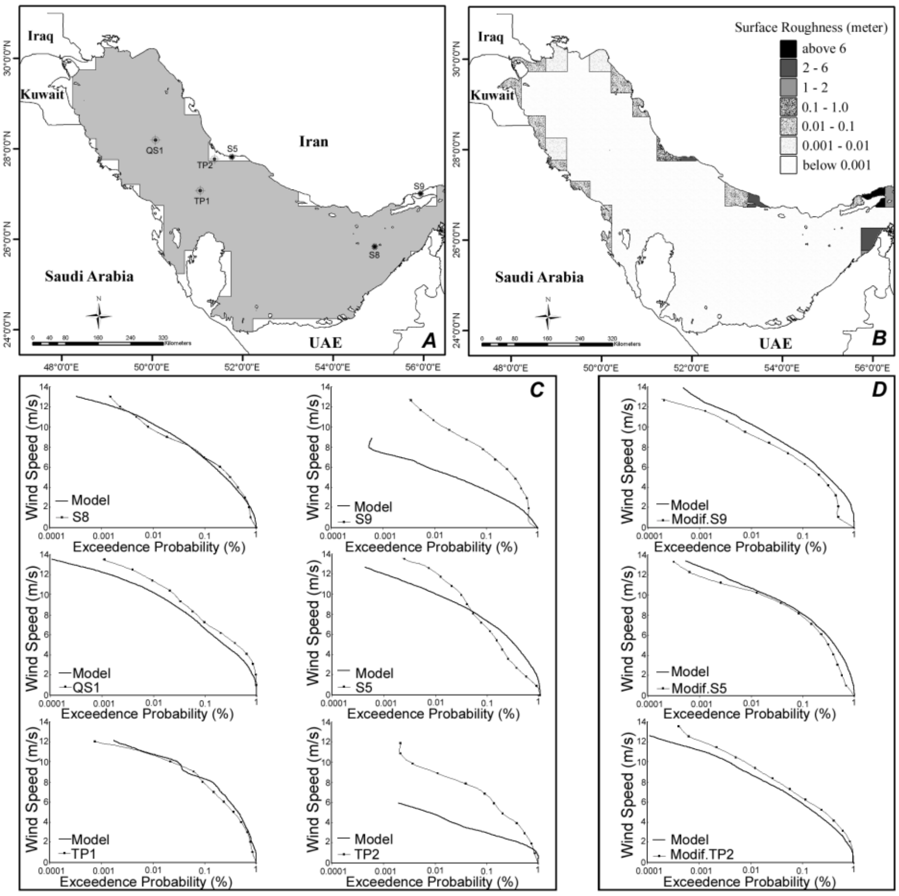


Figure 2. (a): Land mask, and (b): Surface roughness of ECMWF-Operational over the Persian Gulf. (c): Exceedence probability plots of in situ and satellite measurements (TP1, TP2: Topex/Poseidon; QS1: Quick scat). For details of the stations refer to Table 2. (d): Exceedence probability plots of Figure C after ECMWF data transformation based on Weisse and Feser (2003) method.

The wave model was calibrated using in situ wave measurements from Iranian territorial waters [Figure 1]. The wave height of storm events was under-prediction in the model results. The regression analysis was performed for modification of waves exceeding 0.5m in height. The corrected outputs were evaluated using in situ measurements and satellite data. Fig 3 shows typical time-series of Significant Wave Height (Hs), zero-crossing period (TZ) and mean wave direction (MWD) for buoys established in the Iranian coastal areas. Table 3 shows the statistical parameters of all modeled data and higher waves (Hs > 0.5 m). It is observed that the model predicts the wave parameters very well. However, Statistical results were compared with the two well-known references from Cox and Swail [21] in Global reanalysis of Ocean Waves (GROW) based on NCEP/NCAR wind fields, and Caires et al. [22] in ERA-40 project. This comparison shows that all the derived values are within the acceptable range for both offshore and nearshore data. Scatter plots are very suitable for assessment of the results. These plots help to visualize the difference and deficiency of datasets. Figure 4 shows the scatter plots of the model results and the in situ and satellite measurements. The simulated data shows a good agreement with the observations at low sea state, while some peaks are slightly underestimated in offshore area. To present the accuracy of the model, the Average Relative Error (ARE) [23] were calculated for all data and for higher waves (Hs > 0.5 m) [Table 4] in nearshore and offshore locations [Table 4]. The results show that the overall accuracy is more than 80% for all simulated data, and the waves with Hs>0.5m show higher accuracy over the whole Persian Gulf.

In order to get the best results from the model, the output files are needed to be converted into diagrams or graphs so that the interpretation and the comparison of different datasets can be achieved easily, which is a way of checking the accuracy of the simulation. The integration of numerical modeling and Geographical Information System (GIS) recently evolved from a relationship of mere exchanging of output files to more intimate integration [24]. In this study, integration consists of having GIS capabilities and full datasets of observed and modeled data through an object-oriented GIS-based user friendly software, which is the main product of this study, and called Iran Wave Atlas (IWA). IWA covers all the results of the wave simulation and provides a comprehensive geodatabase of specification of full range of normal and extreme wind and wave design data required engineering and environmental processes on the scale of grid systems adopted. The ESRI's commercial software component called ArcObject has been used for programming in IWA development, which provides the GIS capability for this software [24]. IWA uses the ArcMarine Data model [25] for its database and relating it to the GIS component.

The main outputs of the model in this study are time-varying quantities of scalar and vector values. The vector and scalar quantity tables further define the mesh points so that data have been stored depending on its scalar or vector nature, respectively. IWA is able to relate these data with the spatial objects performing the grid cells and measuring points through the object oriented classes related to the geodatabase. The various parameter objects such as wave height, wave period, and wind speed were designed as a lookup table for all parameter which have been stored in the geodatabase. The parameter table stores basic attributes describing the parameters. Time-series value of each parameter also stored in the scalar and vector quantity tables which could be accessed in relation to the parameters table. These tables can be approached in various ways. When users query the table or spatial objects for a specific parameter or a geographic location, access is provided through the relationship classes to the actual time-series values. Likewise, when investigating specific features and data values, the same set of relationship classes provides access to the parameter table and to information describing the data values [Figure 5]. The feature classes and their relationships provide several access routes to the data. The extracted data can be rendered and visualize as scalar or vector spatial display, time-series graphs, contour maps, wind and wave rose diagrams and statistical graphs. Figure 6 shows the main interface page, and some data analysis products of IWA software.

Table 3. Statistical values of hind-casted wave height in this study compared with global standards.

	Buoys		Satellite		Standard Rang	
Param.*	All	Hs>0.5	All	Hs>0.5	*	**
Bias (m)	-0.06	-0.04	0.07	0.10	-0.32 – - 0.85	-0.44 – 0.02
RMS (m)	0.22	0.24	0.35	0.38	n/a	0.31 – 0.71
CC	0.86	0.71	0.85	0.83	0.67 – 0.93	0.82 – 0.95
SI	0.39	0.25	0.40	0.30	0.17 – 0.60	0.13 – 0.32

*- Cox and Swail (2001)
**- Caires et al. (2002)

4. Discussion and Conclusion

As noted above, a 3rd generation of spectral wind-wave model based on unstructured meshes has been used for 10 years (2000-2010) wave hindcast of Persian Gulf. The approaches are based on modified operational ECMWF wind field and in situ and satellite observations over the whole basin. Statistical evaluations show that the results of this study have more than 80% agreement with direct observations, and the difference between similar time-series data are noticeable low. Similar works have been done before

Table 4. Average Relative Error (ARE%) of the hind-casted wave height in the Persian Gulf.

	Compared with Buoys in Nearshore		Compared with Satellite measurements in offshore	
	All	Hs>0.5 m	All	Hs>0.5 m
ARE%	12	8	19	18

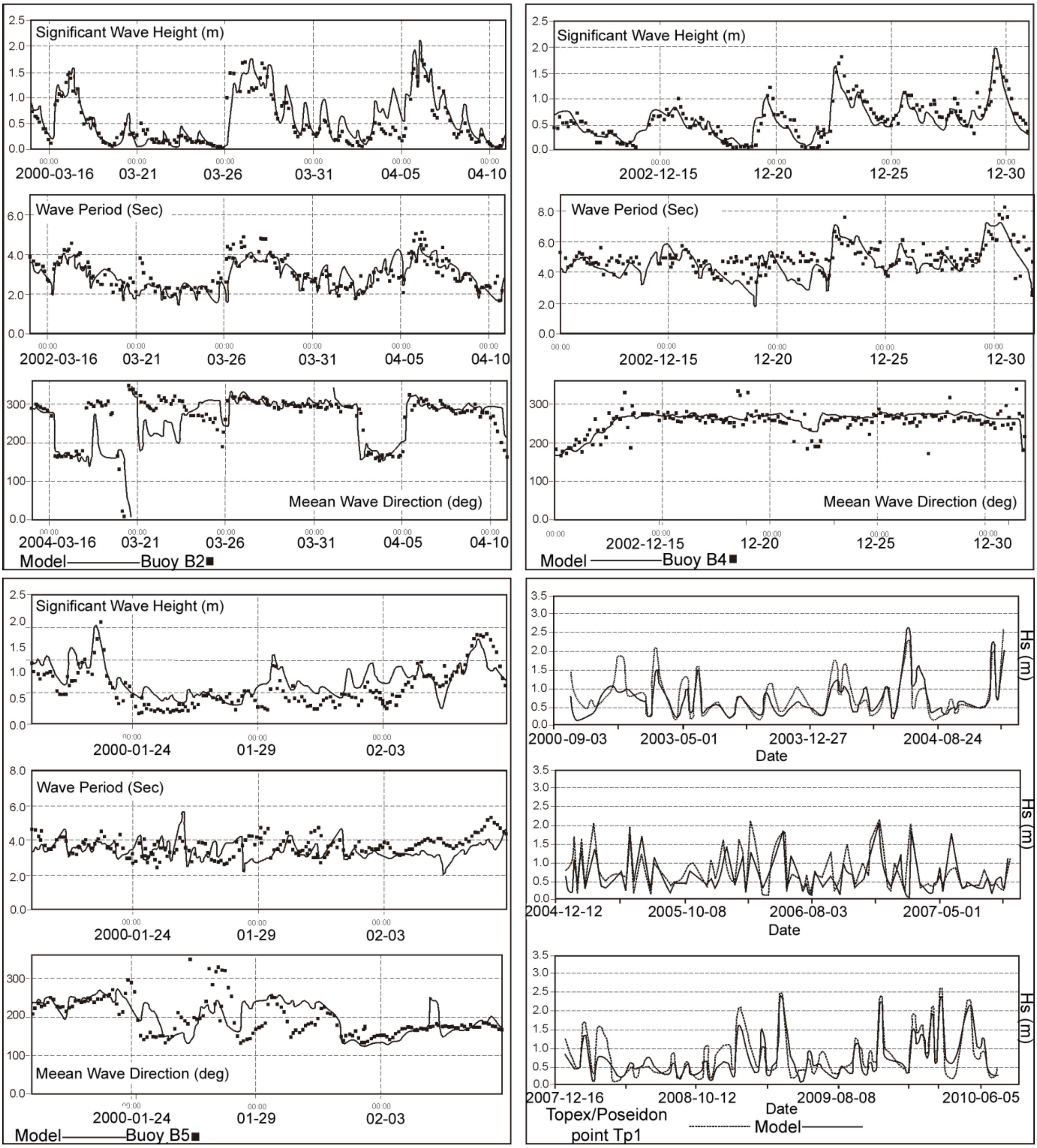


Figure 3. Time-series plots of significant wave height, wave period and mean wave direction of model and selected buoys and Satellite measurements. For details of buoys refer to the Table 2.

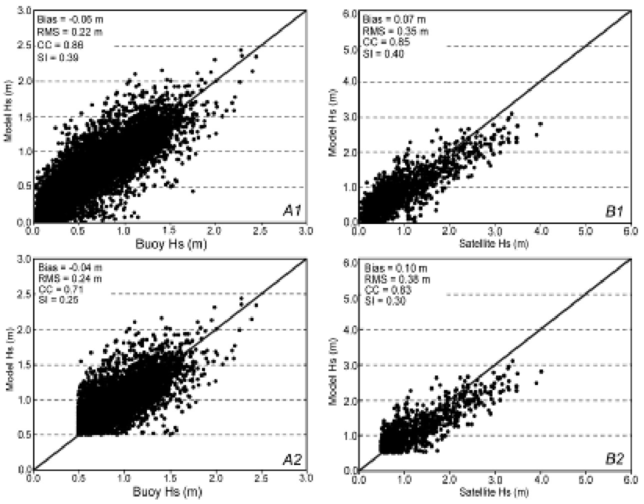


Figure 4. Scatter plots of modeled wave height versus buoys and satellite measured wave heights. A1, B1: all datasets, A2, B2: Hs > 0.5 m.

for this area [3, 5]. These studies have used 3rd generation models with different approaches to this study. Figure 7 shows the comparison of the timeseries data of this study with another available similar work [5]. However, this comparison shows that the results of these two projects are in good agreement especially at extremes, although some differences exist. Finally, it could be concluded that the 3rd generation wave hindcast models with valid and reliable wind field and other required data, can present an authentic wave climate of the Persian Gulf. Some differences between these two studies and similar another works should be due to the different approaches and also validation data applied to the models. It is strongly recommended that all adjacent countries around the Persian Gulf establish in situ measuring networks for wave and the other hydrodynamic parameters.

In order to achieve a practical and easy to use hydrodynamic database for coastal engineering applications, it is accepted that the outputs of the hydrodynamic models must be converted to information. To do this, data management systems must be considered as one of the essential parts of the hydrodynamic atlases. Available wave simulation models have irregular or commercial data formats which are not in international standards for data sharing through the operational data management systems. Hence, all datasets (basic, in situ and model results) should be converted into operational and easy to use databases. In addition, GIS is a powerful tool for data management and analysis that should be used in data management systems. Integration of GIS with relational database management systems (RDBMS) could be a good solution. This study presents a methodology for development of the wave atlas software for the Persian Gulf. The results of this study are available in this software and enable us to perform wave hindcast models and forecasting of wind and waves for this region.

Parameter

Parameter ID	Name	Description	Quantity	Unit	Significant digits
1	Hs	Wave Height	Scalar	Meter	3
2	Tp	Time Period	Scalar	Sec	1
3	Wind Vector	Vector Components of Wind	Vector	m/s	1

Scalar Quantity

Feature ID	Parameter ID	TimeValue	DataValue
8115370	2	01-05-2000 04:00:00	0.324
8115370	1	01-05-2000 04:05:00	2.2
8115370	2	01-05-2000 04:10:00	0.319
8115370	1	01-05-2000 04:15:00	2.7
8115370	2	01-05-2000 04:20:00	0.321
8115370	1	01-05-2000 04:25:00	3.1
8115370	2	01-05-2000 04:30:00	0.322

Vector Quantity

Feature ID	Parameter ID	TimeValue	X Component	Y Component
7005230	3	01-05-2000 04:00:00	2.32	-25.1
7005230	3	01-05-2000 04:05:00	2.76	-23.8
7005230	3	01-05-2000 04:10:00	2.22	-25.9
7005230	3	01-05-2000 04:15:00	1.87	-24.5
7005230	3	01-05-2000 04:20:00	2.12	-19.0

Mesh Point

Shape	FeatureID	FeatureCode	IPosition	Jposition	Kposition	MeshID	PointType
Point	3037986	2_42792	23	12	0	2	Grid Point
Point	3037982	2_42795	24	12	0	2	Grid Point
Point	3037985	2_42712	55	34	0	3	Grid Point
Point	3037921	2_42796	57	34	0	3	Grid Point
Point	3037989	2_42793	58	34	0	3	Grid Point

Mesh

MeshID	TotalPoints	NoOfPointsI	NoOfPointsJ	NoOfPointsK	Dimension
2	1032	43	24	0	Surface
3	1032	43	24	0	Surface

Figure 5. Data model structure of Iran Wave Atlas software. The structure allows users to approach the data from several conditions, either spatially by querying a Mesh for points and then determining the data available, or to find all points of a certain parameter type.

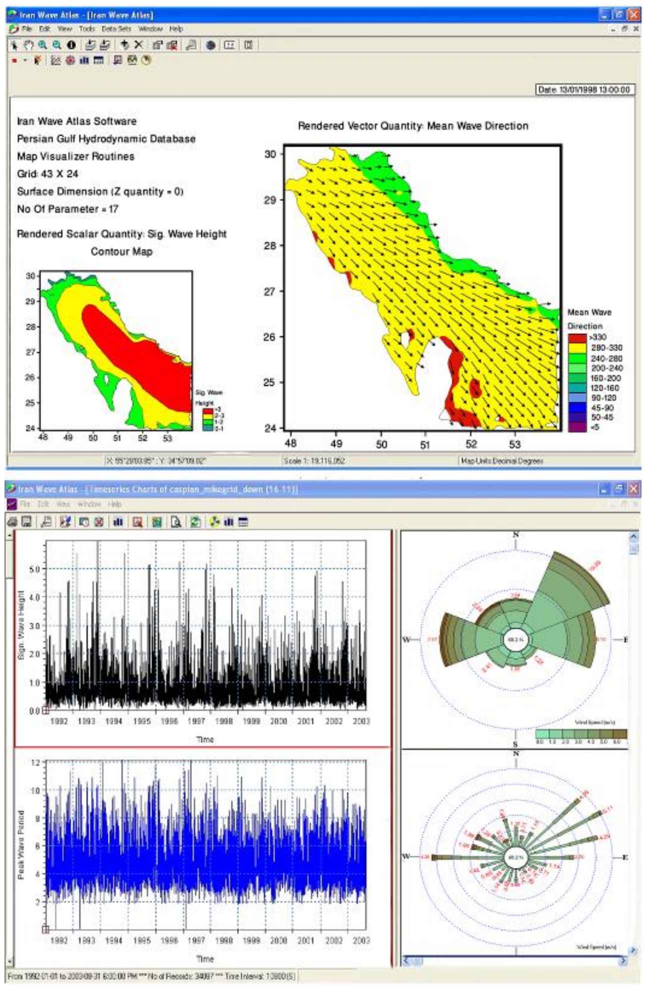


Figure 6. Screen shots of Iran Wave Atlas main page and data products page.

prediction systems at the fleet numerical

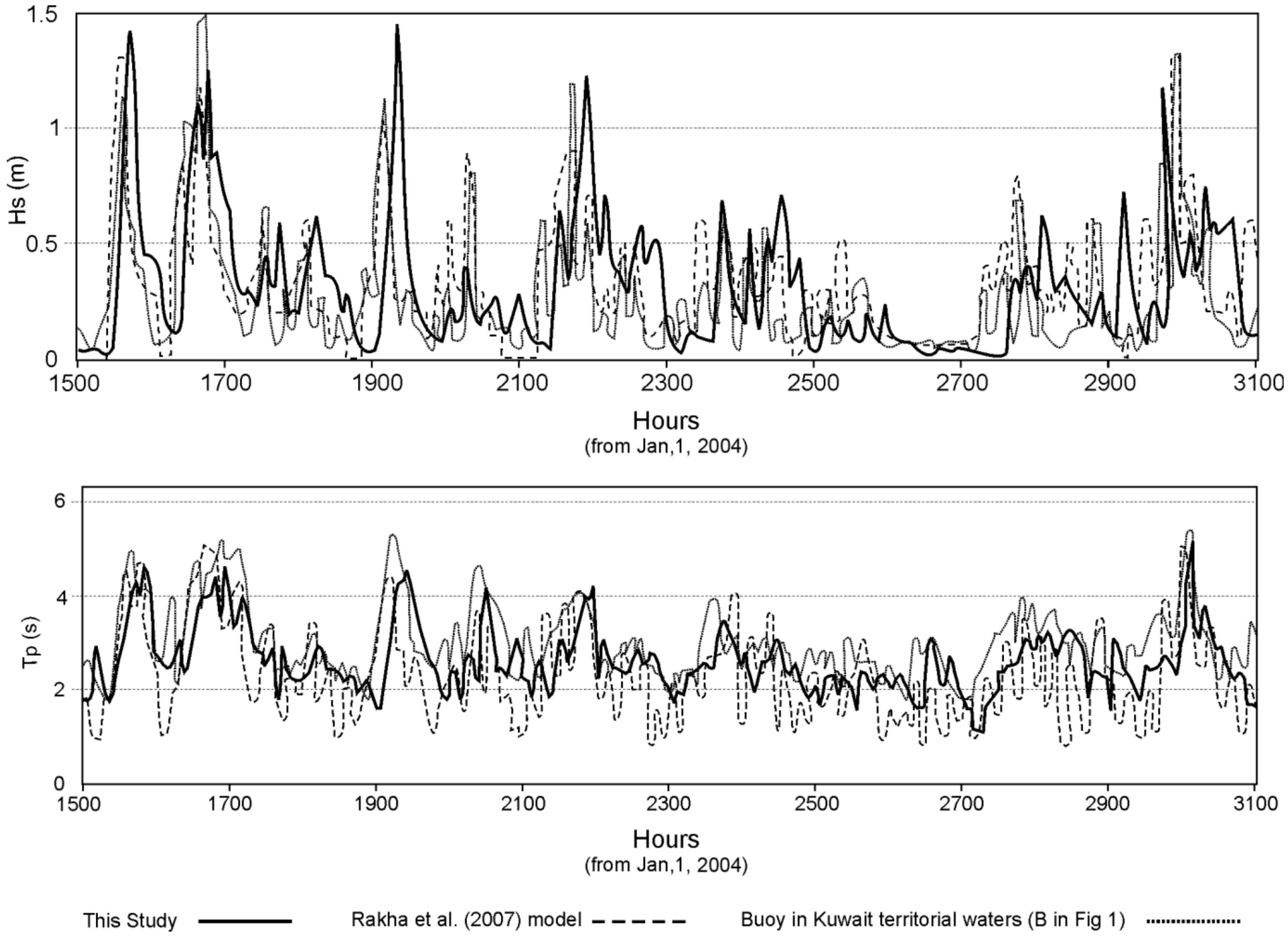


Figure 7. Comparison of the result of this study with Rakha et al. (2007) model and with a buoy in the Kuwait territorial waters (B in Figure 1).

oceanography center, Weather and forecasting, vol. 7, no. 2, pp. 273-279.

8. References

[1] K. O. Emery, (1956). Sediments and water of Persian Gulf, AAPG Bulletin, vol. 40, no. 10, pp. 2354-2383.

[2] B. H. Purser, and E. Seibold, (1973), The Principal Environmental Factors Influencing Holocene Sedimentation and Diagenesis in the Persian Gulf, *Persian Gulf*, Purser, BH (ed), Berlin, pp. 1-9.

[3] A. El-Gindy, and M. Hegazi, (1996), Atlas on Hydrographic conditions in the Arabian Gulf and the upper layer of the Gulf of Oman, University of Qatar Press, 170pp,.

[4] J. W. Kamphuis, (2010). Introduction to coastal engineering and management: World Scientific Publishing Company Incorporated.

[5] K. Rakha, K. Al-Salem, and S. Neelamani, (2007), Hydrodynamic atlas for the Arabian Gulf, Journal of Coastal Research SI50, pp. 550-554.

[6] G. Bayler, and H. Lewit, (1992), The Navy operational global and regional atmospheric prediction systems at the fleet numerical oceanography center, Weather and forecasting, vol. 7, no. 2, pp. 273-279.

[7] S. Caires, A. Sterl, J. Bidlot et al., (2002), Climatological assessment of reanalysis ocean data, 7th Int. Workshop on Wave Hindcasting and Forecasting (Canada, Toronto), pp. 1-12.

[8] OCEANOR, (1999), World Wave Atlas: User’s Manual. Version 2, Norway, 33 p.

[9] H. L. Tolman, (1998), Validation of NCEP’s ocean winds for the use in wind wave models, Global Atmosphere and Ocean System, vol. 6, no. 3, pp. 243-268.

[10] A. Sterl, G. Komen, and P. Cotton, (1998), Fifteen years of global wave hindcasts using winds from the European Centre for Medium-Range Weather Forecasts reanalysis: Validating the reanalyzed winds and assessing the wave climate, *Journal of Geophysical Research*, vol. 103, no. C3, pp. 5477-5492.

[11] L. Cavaleri, and L. Bertotti, (2004), Accuracy of the modelled wind and wave fields in enclosed seas, Tellus A, vol. 56, no. 2, pp. 167-175.

[12] F. Al-Yamani, J. Bishop, E. Ramadhan, M. Al-Husaini, and A. AL-Ghadban, (2004), Oceanographic Atlas of Kuwait's Waters, Kuwait Institute for Scientific Research Report, 203 p.

[13] W. Elshorbagy, M. H. Azam, and K. Taguchi, (2006), Hydrodynamic characterization and modeling of the Arabian Gulf, Journal of waterway, port, coastal, and ocean engineering, vol. 132, no. 1, pp. 47-56.

[14] K. Al-Salem, K. Rakha, W. Sulisz *et al.*, (2005), Verification of a WAM Model for the Arabian Gulf. pp. 27-29.

[15] Young, I.R., (1999), Wind generated ocean waves, *Elsevier*, 288 P.

[16] Harmancioglu, N.B., Alpaslan, M.N., Ozkul, S.D. and Singh, V.P., (1997), Integrated approach to environmental data management systems, *proceedings of the NATO advanced research workshop on integrated approach to environmental data management systems*, Sept. 16-20,1996, Izmir, Turkey, Kluwer academic publishers, NATO ASI Series, 2. *Environment*, vol. **31**, 546 P.

[17] Singh, V.P., (1995), Watershed modeling, in: *Computer models of watershed hydrology*, *water resources publications*, Littleton, ch. 1, pp. 1-22.

[18] HDI Water & Environment, (2003), Mike 21 Spectral Wave Model: User Guide, Denmark, 84p.

[19] J. M. Hubertz, D. B. Driver, and R. D. Reinhard, (1991), Wind waves on the Great Lakes: a 32 year hindcast, Journal of Coastal Research, pp. 945-967.

[20] R. Weisse, and F. Feser, (2003), Evaluation of a method to reduce uncertainty in wind hindcasts performed with regional atmosphere models," Coastal Engineering, vol. 48, no. 4, pp. 211-225.

[21] A. T. Cox, and V. R. Swail, (2001), A global wave hindcast over the period 1958–1997: Validation and climate assessment," Journal of Geophysical Research, vol. 106, no. C2, pp. 2313-2329.

[22] Caires, S., Sterl, A., Bidlot, J.R., Graham, N. & Swait, V., (2002), Climatological assessment of reanalysis ocean data, in *Proc. 7th Int. Workshop on Wave Hindcasting and Forecasting*, Canada, pp. 1-12.

[23] Z. Liu, and P. Frigaard, (2001), Generation and analysis of random waves, Laboratoriet for Hydraulik og Havnebygning, Instituttet for Vand, Jord og Miljoteknik, Aalborg Universitat.

[24] ESRI, (2000), Developing Applications with ArcInfo: An Overview of ArcObjects, An ESRI White Paper, 75 p.

[25] D. J. Wright, M. J. Blongewicz, P. N. Halpin *et al.*, (2008), *Arc Marine: GIS for a blue planet*: Taylor & Francis.

INTERNATIONAL JOURNAL OF COASTAL & OFFSHORE ENGINEERING

IJCOE Vol.6/No. 2/Spring 2021 (56-69)

Available online at: www. Ijcoe.org

Dynamic Stability Analysis of High-Speed Trains Moving over Sea-Cross Bridge subjected to Rail Irregularities

Amin Razzaghi Kalajahi[1], Morteza Esmaeili[2*], Jabbar Ali Zakeri[3]

[1] *School of Railway Engineering, Iran University of Science and Technology, Tehran, Iran; amin_razzaghi@rail.iust.ac.ir*
[2]* *School of Railway Engineering, Iran University of Science and Technology, Tehran, Iran, m_esmaeili@iust.ac.ir*
[3] *School of Railway Engineering, Iran University of Science and Technology, Tehran, Iran, zakeri@iust.ac.ir*

ARTICLE INFO

Article History:
Received: 16 Oct. 2020
Accepted: 29 Apr. 2021

Keywords:
High-Speed Train
Bridge
Wave
Stability

ABSTRACT

Dynamic performance of the 3D train–bridge system (TBW model) subjected to different hydrodynamic loads and applying AAR track irregularity is established in this study. By taking a continuous bridge (32 + 48 + 32) m with box girders as a case study, the dynamic responses of the bridge which is under train passing and subjected to several sea hydrodynamic loads are analyzed. The substructure of the bridge includes four concrete solid piers with rectangular sections and piers are fixed at seabed. Piers and decks are designed and analyzed based on dynamic finite elements methods, and hydrodynamic forces are applied on piers according to Morison's theory. Also, car body is modeled by a 27-DoFs dynamic system. Model validation has been performed with another research by considering vessel collision load. Then, the dynamic responses of the bridge and the running safety indices of the train on the bridge under several types of sea wave states when train speed is 300 km/h analyzed. Results of TBW's sensitive analyzes have shown the importance of sea-states conditions for train safe and comfortable running. Also, irregularity has an obvious effect on the dynamic responses of the bridge. It has greater effect on vertical acceleration and displacement than horizontal ones in presence of hydrodynamic load. Combination of these two phenomena (wave and irregularity) jeopardizes the running safety of train when crossing the bridge.

1. Introduction

Today, the use of rail transportation system has been accepted as one of the best transportation modes in the most developed countries. In these countries, high-speed trains play a major role in passenger transportation management and are always in the center of attention. One of the important structures in the railroad are bridges that are constructed with different length and spans over the rail routes and make the traffic of the rail vehicles possible with acceptable quality [1]. Bridges are one of the most important railway structures that may need to be built in challenging locations, one of these is the construction of bridges to cross the waterways safely. River/Sea crossing bridge is one of the common infrastructures for the extension of rail from the mainland to the islands or coastal areas [2]. The behavior of bridges is affected by different loads and special attention needs to be paid to this. The loads on the railway bridges vary in terms of axle load, running speed and volume of the yearly traffic and affect the behavior of the railway bridges, so extensive studies have been carried out in this regard. Dynamic bridge-train interaction is one of the topics that has attracted the attention of railway engineers over the past thirty years. Train operational parameters are the most important factors affecting the behavior of bridges, consequently many studies have been carried out to resolve the vibration problems and ensure the vehicle–bridge coupling system's performance [1], [3]–[5]. Other Studies on the horizontal displacements in structural frames under vertical forces are discussed [6]. Various studies have been conducted to simulate the behavior of bridges against earthquakes and winds [7], [8]. Further appropriate research has been done on the lateral dynamic behavior of railway bridges [9]. Other researches on how to model train-bridge interactions using two models of moving load or mass-spring model have been done [10]–[12], and have provided suggestions on how to model the train-bridge interactions, and have presented results about ineffectiveness of modeling all components of bridges with spans greater than 15 m [13], [14]. Other articles have been written about bridge behavior under train moving load with considering bridge's damping ratio, span length and deck materials [15]. Train moving load on bridge is also performed by ANSYS software [16]. A 3D FEM which is employed in Abaqus finite element software to model and analyze the bridge and train while considering the interaction between them using the Hertz theory has been presented [1].

As is clear, bridges are indispensable structures for crossing rivers, bays and other railway or highway lines, while sometimes they also become man-made obstacles against water flow or traffic underneath. With the rapid expansion of the infrastructure network in the past decades, more crossings are generated. They are the cause of many bridge collapse accidents due to vessel, vehicle and other collisions [17], [18]. The factors producing bridge collapses can be divided into two categories: man-made and natural. The man-made factors include design faults, construction mistakes, collisions (by vessels, automobiles and trains), overload, etc. The natural factors include earthquakes, water flow (flood, scouring, etc.), wind, collisions (by floating floes or other objects), environmental deterioration (temperature, corrosion, etc.), etc. Earthquakes and strong crosswinds may jeopardize the running safety of the vehicle, especially when it crossing a viaduct. Many studies carried out regarding the dynamic response of a train-bridge coupling system subjected to crosswinds and earthquakes in the presence of track irregularity levels [19]–[22]. Also according to importance of trains running safety under vessel-bridge or ice-bridge collision, numerical analyzes and experimental tests have been carried out [17], [23], [24].

One of the topics that have not been considered during the study of railway bridges research background is the lack of consideration of coupled high-speed train and bridge system subjected to wave hydrodynamic load. Many structural failures and vehicle accidents due to extreme wave have been reported in previous studies [25]–[27]. Regarding to importance of hydrodynamic failures on coastal bridges, experimental tests for a large-scale bridge superstructure model have been done [28]. Wave hydrodynamic lateral force components and vibration may make troubles to the vehicles running on the deck. Also when train crosses over a bridge, asymmetric loading is applied to the bridge which can laterally move the structure. Train moving load on two-lane bridge can cause lateral displacement [29]. These displacements and accelerations could be increased with the change in wave load and train speed, and may make trouble in riding comfort and running safety according to domestic or international codes' criteria. Many studies have been conducted to determine the amount of wave force applied to marine structures [30]–[32]. Several analyzes have been carried out in previous studies about coupling hydrodynamic force with other phenomena such as: earthquake, wind, tide level and etc. [32]–[35].

For a bridge, the external load considered in the design may be a vessel collision, an ice-floe collision, a vehicle passing, a train passing, or hydrodynamic loads. However, few of current research studied about considering wave hydrodynamic load on railway bridges. Moreover, sometimes more than one of external loads like train passing and wave hydrodynamic load may occur simultaneously. Since various external loads have different properties, the dynamic responses of the bridge and their effects on the running safety of high-speed trains might be different. In this study, running safety means that acceleration and displacement values are allowed regarding to Chinese and European codes in both vertical and lateral directions, which are introduced in next section as railway bridge safety criteria.

This article presents a 3D train–bridge–wave (TBW) interaction model. A continuous railway bridge with (32 + 48 + 32) m box girders is considered as a case study. This bridge is located in China and some research like vessel and ice-floe collision have been carried out which is proper for validation with TBW model [18], [23]. The train used in the validation is selected based on the passing train in the field test [1], [36].

Most studies carried out in the field of bridge-train interaction are associated with simplifying assumptions like moving load or moving mass. However, considering the importance of high-speed railway bridges, these bridges need a higher precision control. In this paper, a two-lane bridge, a high-speed train and the interactions between them are modeled with considering various speeds of train (V). Moreover, in 3D TBW model, hydrodynamic loads with several wave heights (Hs) and periods (T) have been considered according to Morison equation [31]. When hydrodynamic load acts on bridge piers, it may cause dislocation, uneven deformation, displacement or acceleration, which can affect the bridge's response to train passing.

Several scenarios by varying wave parameters such as wave height and wave period (Hs, T) have been carried out in this paper. Finally vertical/lateral acceleration (Ay, Az) and vertical/lateral displacement (Uy, Uz) values of railway bridge deck are compared with the permissible values regarding to Chinese and European codes, and the values of safe and comfort speed according to environmental conditions (wave parameters) are determined in different scenarios.

Moreover, track irregularities are an important source of excitation for both the bridge and the vehicle. The irregularities are deviations of the rail from the design geometry, which is one of the most significant load amplification factors in railway track systems [37]–[39]. As mentioned, train run excites the track through the wheel-rail contact mechanisms. Under certain conditions of track, the load coming from the train could be significantly higher than the static value due to irregularity. In last section of this study, TBW model is developed by applying rail irregularity and additional sensitive analyzes are done to evaluate the performance of high-speed train and bridge system under the excitation of wave hydrodynamic load and rail irregularity. Fourth quality level of Association of American Railroads [39] is applied on TBW model to consider irregularity.

2. Railway Bridge Safety Criteria

Among the restrictive criteria for safe and comfort passage of high-speed railway bridges are vertical and lateral accelerations and displacements of decks, which have been referred in various sources such as Chinese and European codes. So as mentioned, several scenarios by varying wave parameters (Hs, T) and passing train with speed of 300 km/h have been carried out in this paper. Finally vertical/lateral acceleration (Ay, Az) and vertical/lateral displacement (Uy, Uz) values of railway bridge are compared with the permissible values regarding to Chinese and European codes [22], [40]–[43], and the values of safe and comfort speed according to sea states (wave parameters) are determined in these scenarios.

2.1. China's high-speed railway bridges criteria

China's high-speed railway bridges criteria for displacement and acceleration, which have been used to study safe and comfort passing in this study [44], are as follows:

(i) The maximum allowable vertical displacement of the deck is determined by Table 1 for different speeds.

Table 1. Maximum allowable vertical displacement of bridge

Range of Span / Designed Speed	L ≤ 40 m	40 m < L ≤ 80 m	L > 80 m
250 km/h	L/1400	L/1400	L/1000
300 km/h	L/1500	L/1600	L/1100
350 km/h	L/1600	L/1900	L/1500

(ii) The maximum allowable lateral displacement of the deck (Uz) is determined by Eq. (2.1) according to length of span (L).

$$U_z \leq \frac{L}{4000} \tag{2.1}$$

(iii) The maximum vertical and lateral acceleration of the deck (Ay, Az) are determined as 0.13g and 0.1g, respectively.

Also, for better review, other codes such as European codes and ISO criteria have been used to study safe and comfortable passing in this study.

2.2. European's high-speed railway bridges criteria

(i) According to Euro Codes, the maximum allowable vertical displacement of the deck (δ) is determined by Fig. 1.

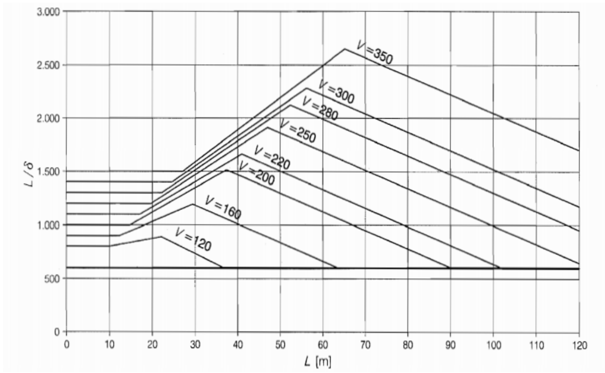


Fig 1. Maximum allowable vertical displacement of bridge [15], [40], [41]

(ii) According to Euro Codes, the maximum allowable lateral displacement of the deck (Uz) is determined by Eq. (2.2) according to length of span (L) and maximum allowable horizontal rotation (r) as shown in Table 2.

$$U_z \leq \frac{L^2}{8 * r} \tag{2.2}$$

Table 2. Maximum allowable lateral rotation of bridge [15], [40], [41]

Speed (km/h)	Single Deck	Multi Deck Bridge
V ≤ 120	1700	3500
120 < V ≤ 200	6000	9500
V > 200	14000	17500

(iii) According to Euro Codes and ISO, the maximum vertical and lateral acceleration (Ay, Az) are determined as 1.25 m/s^2 for the good safety and comfortable train passing on bridge [40], [41], [43], [45], [46].

Comparing the two codes with each other, it can be seen that in general, the Chinese code offers more restrictive criteria than the European codes. However, both codes have been used to better investigate the present research outcomes in the next sections.

3. Interaction Models Development

3.1. Train-bridge interaction model

The China high-speed train and bridge models are used in this study. A 3D FE model is employed in Abaqus finite element software to model and analyze the bridge and train while considering the interaction between them using the Hertz theory [47]. Next, Abaqus model is validated by comparing the lateral acceleration of bridge under vessel collision load which is done by Xia et al.[18]. The 3D Train-Bridge-Wave model (TBW) is then used to assess sensitivity analysis according to wave height (H) variations (when train speed is considered 300 km/h) to monitor train riding comfort and running safety according to code's criteria.

The train model is composed of locomotive and wagon. Each locomotive or wagon consists of a car body, two bogies, four wheel-sets, and the spring and damping connections between the three components. The car body configuration and train's mechanical properties and dimensions are presented according to China high speed train in Fig. 2 and Table 3, respectively. Also, cross section of the concrete box deck is illustrated in Fig. 3.

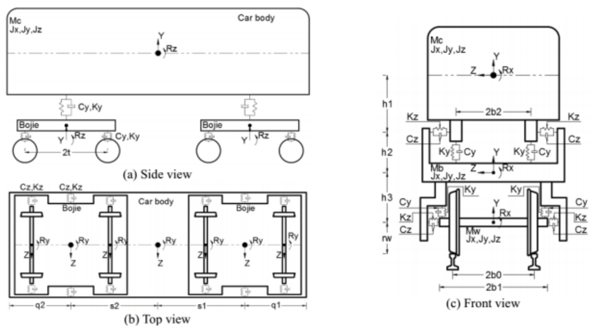


Fig 2. Car body configuration [48]

Table 3. Train's mechanical properties and dimensions

DESCRIPTION	NAME	UNIT	POWER CAR	PASSENGER CARS
CAR-BODY DIMENSIONS	s1; s2; q1; q2; h1	m	5.73;5.73;6.8;3.75; 0.75	9;3.75;3.75;0.75
MASS OF CAR-BODY	Mc	ton	63.98	43.82
CAR-BODY INERTIA MOMENTS	Jx; Jy; Jz	ton.m2	59.4; 2505.3; 2485.4	23.2; 2100; 2080
MASS OF BOGIE	Mb	ton	3.434	3.04
BOGIE INERTIA MOMENTS	Jx; Jy; Jz	ton.m2	1.766; 2.453; 4.905	1.580; 2.344; 3.934
SECONDARY SUSPENSION STIFFNESS	Kz; Ky	KN/m	297.2; 1245.87	176; 265
SECONDARY SUSPENSION DAMPING	Cz; Cy	KNS/m	98.1; 98.1	39.2; 45.12
SECONDARY SUSPENSION DIMENSIONS	b2; h2	m	1.23; 0.42	1.23; 0.42
PRIMARY SUSPENSION STIFFNESS	Kz; Ky	KN/m	2452.5; 1226.25	2350; 590
PRIMARY SUSPENSION DAMPING	Cz; Cy	KNS/m	98.10; 29.43	58.86; 19.62
MASS OF WHEEL-AXLE	Mw	ton	1.776	1.776
WHEEL-AXLE MOMENT	Jx; Jy; Jz	ton.m2	1.138; 1.138; 0.00785	1.138; 1.138; 0.00785
PRIMARY SUSPENSION & WHEEL	b0; b1; h3; t; rw	m	0.75; 1; 0.2; 1.25; 0.455	0.75;1;0.2;1.25;0.455

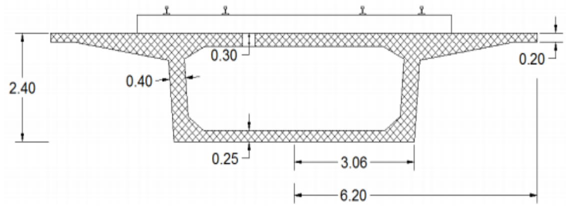


Fig 3. Cross section of the concrete box deck

The following assumptions are made in modeling the train vehicle:

(i) The car body, bogies and wheel-sets in each vehicle are regarded as rigid components, neglecting their elastic deformation during vibration as shown in Fig. 4.

(ii) The connections between car body, bogies and wheel-sets are represented by linear springs and viscous dashpots (as shown in Figs. 5 and 6).

(iii) Each train body has five degrees-of-freedom (DoFs). They correspond to the lateral displacement, the roll displacement, the yaw displacement, the vertical displacement, and the pitch displacement. Each bogie on the vehicle has five DoFs: the lateral displacement, the roll displacement, the yaw displacement, the vertical displacement, and the pitch displacement. For each wheel under the bogie, three DoFs are considered: the lateral displacement, the roll displacement, and the vertical displacement. Thus, the train is modeled in TBW for each vehicle with 2-bogies and 4-axles can be modeled by a 27-dof dynamic system, as shown in Fig. 6.

(iv) Regarding to other research [14], in longer spans (L >15m) the dynamic response is not sensitive to track stiffness value, so slab track is not modeled separately and merged with deck as an integrated model. Piers and deck are modeled as 3D deformable solid element with considering concrete specification. Rails are modeled as 3D deformable solid element with considering steel specification and tied on deck, also for considering the interaction between wheels and rails the Hertz theory is used (as shown in Figs. 5 and 6).

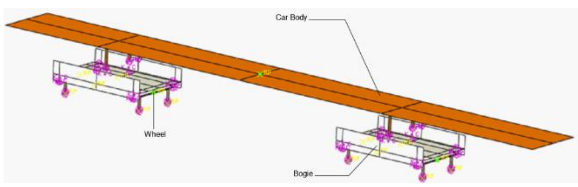


Fig 4. Train 3D model

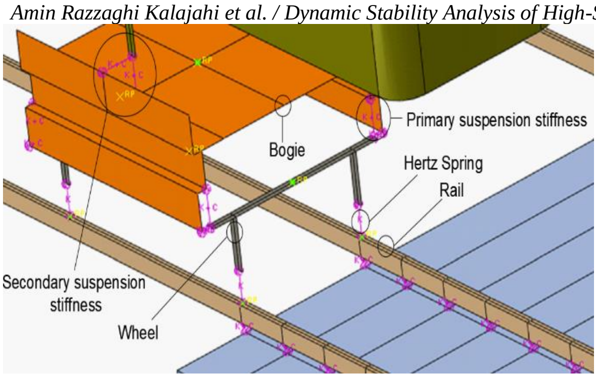


Fig 5. Modeling wheel-rails interaction by hertz spring

(v) The considered bridge is a two-lane continuous with concrete box (32+48+32) m (as shown in Fig. 6). The substructure of the bridge includes four concrete solid piers with rectangular sections (8m x 4.5m) and piers are fixed at seabed. Deck mounted on piers are fixed pot neoprene bearings and the bearings are modeled according to the design [18]. For the fixed bearings, the rotational angle about the transverse axis z of the girder end is free, while the other 3 translational displacements and 2 rotational angles are connected through master-and-slave relations to the pier-top and the damping ratio of the bridge is taken as 2.5 %. The height of piers are assumed 20 m and sea level which is proposed hydrodynamic force interaction with piers is considered at level +15m.

(vi) Train passes the bridge with V=300 km/h.

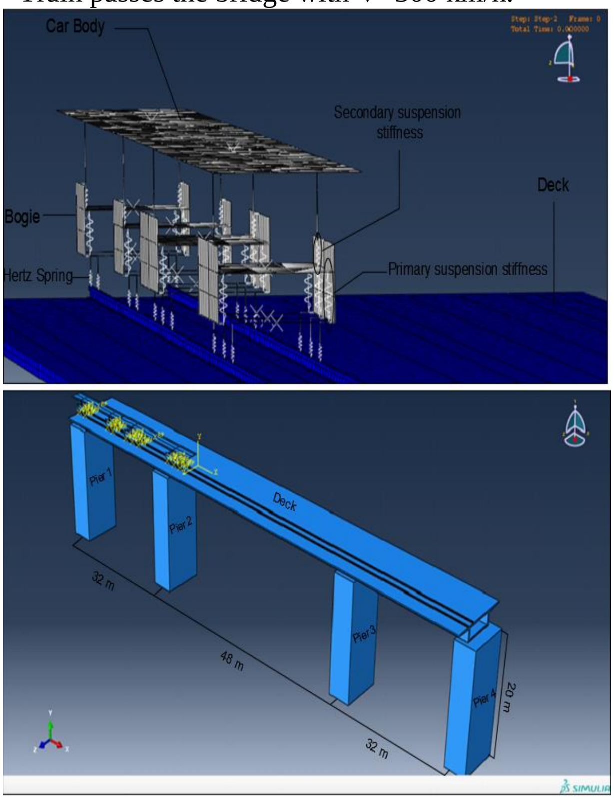


Fig 6. Train-bridge 3D model

Summary of the train modeling method and the definition of its interaction with the bridge is provided in the following steps:

(i) Several 3D models were developed in real dimensions of car-body, bogies and wheels by using 3D discrete rigid shells module in Abaqus.

(ii) Real mass and inertia were assigned for each part of wagon and locomotive according to car-body's specification (which are represented in Table 3).

(iii) Several springs were modeled to connect different parts of car-body to each other by using interaction module of Abaqus. In this model several rigid parts were linked in all directions by primary and secondary springs for considering suspension stiffness and damping (as shown in Figs. 3 and 4).

(iv) All wheels were connected to rails by using interaction module of Abaqus and applying hertz theory.

(v) In addition to define displacement and rotation boundary conditions, velocity boundary condition in x direction was defined to model car-body movement in Abaqus to perform dynamic analysis.

3.2. Hydrodynamic force on pier

Based on the Morison's theory [31], it is assumed that the effect of fluid on the structure is caused by the acceleration field and velocity field, and the effect of structure on the movement of fluid could be ignored. Therefore, the hydrodynamic force (F_{Wave}) acting on the column includes two components (as shown in Equations (3.1)-(3.5)): one is the inertial force (F_I) and the other is the drag force (F_D) on the column due to the effect of viscous and swirl (as shown in Figs. 7).
Morison equation is adopted to calculate the wave forces on the columns, of which the structure diameter or width D is smaller than 0.2 times wave length L.

$$F_{Wave} = F_D + F_I \tag{3.1}$$

$$F_D = \frac{C_d}{2}\,\rho\,A\,u^2 \tag{3.2}$$

$$F_I = C_m \rho V \mathring{u} \tag{3.3}$$

$$F_{Wave} = \frac{C_d}{2}\,\rho\,A\,u^2 + C_m \rho V \mathring{u} \tag{3.4}$$

Here, ρ is the density of the fluid, V is the volume of the submerged structure, A is the area of the column section, u and ů are the absolute velocity and acceleration of the fluid respectively, C_m is the inertia coefficient and C_d is the drag force coefficient of the fluid. The total hydrodynamic force on the unit length (ds) of the column along the Z-axis direction can be expressed as:

$$F_{Hydrodynamic} = \frac{F}{ds} = \frac{C_d}{2}\,\rho\,D\,u^2 + C_m \rho \left(\frac{\pi D^2}{4}\right) \mathring{u} \tag{3.5}$$

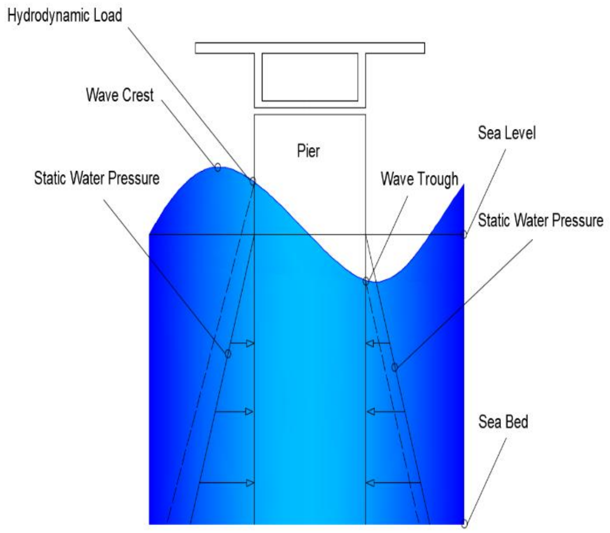


Fig 7. Hydrodynamic force on pier

Table 4. Wave estimation according to wind conditions [49]

Wind Conditions			Wave Size		
Wind Speed in One Direction	Fetch	Wind Duration	Average Height	Average Wavelength	Average Period
56 km/h	518 km	23 h	4.1 m	76.5 m	8.6 sec
74 km/h	1313 km	42 h	8.5 m	136 m	11.4 sec
92 km/h	2627 km	69 h	14.8 m	212.2 m	14.3 sec

Three sea states, sea states I, II, and III, are considered based on three different mean wind speeds U_{Wind} of 56, 74, and 92 km/hr for China Sea area. The characteristics of selected sea states for TBW model are defined in Table 5.

Table 5- Selected sea states for TBW model

Sea States	Hs(m)	Ts(s)
I	4.1	8.6
II	8.5	11.4
III	14.8	14.3

The wave hydrodynamic force is calculated and applied to the Abaqus model as harmonic forces according to the marine conditions as mentioned in Table 5 and Eq. (3.5). The assumed values for the coefficients Cd and Cm are 1 and 2, respectively [30]–[32].

3.3. Train - bridge – wave model

As mentioned previously, wave hydrodynamic lateral force makes troubles to the trains running on the deck. Also when train crosses over a bridge, asymmetric loading is applied to the bridge which can move the structure (as shown in Fig. 8). The wave hydrodynamic force is calculated and applied to the Abaqus train-bridge-wave model (TBW) according to the marine conditions mentioned in Table 5 and using Eq. (3.5). Vertical and lateral displacements and accelerations are increased with the change in wave load and train speed, and may make trouble in riding comfort and running safety according to code's criteria.

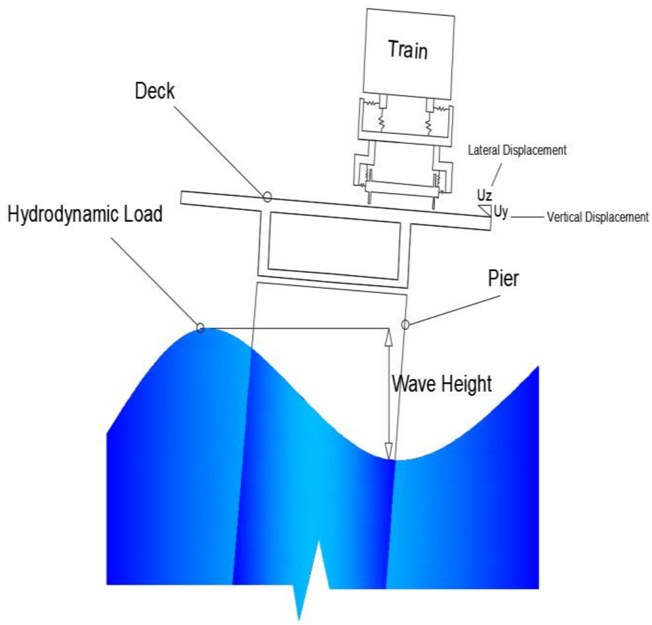


Fig 8. Pier lateral movement due to wave force

Bridge, Train and Hydrodynamic load modeling are performed using the FEM in Abaqus software. Sea states I, II, and III, are applied to assess sensitivity analysis. As mentioned, substructure of the bridge includes four concrete solid piers with rectangular sections (8m x 4.5m) and piers are fixed at seabed. The height of piers are assumed 20 m and sea level which is proposed for hydrodynamic force interaction with piers is considered at level +15m. The wave direction (Z-axis) is assumed to be perpendicular to the train passing direction (X-axis). Also, hydrodynamic load is applied to bridge piers simultaneously and train passes the bridge with speed of 300 km/h to sensitivity analysis. Eight scenarios with wave and track irregularity variation have been applied in this study for considering effect of presence or absence of wave and track irregularity for train running on bridge are performed. Full 3D Train-Bridge-Wave (TBW) model is shown in Fig. 9. As mentioned, China high speed railway code and European code are used for assess riding comfort and running safety. In order to make a good judgment with respect to the importance of wave reaching time to the piers, as the worst scenario each maximum value of hydrodynamic loads are applied on piers at the time when the train arrives middle of deck.

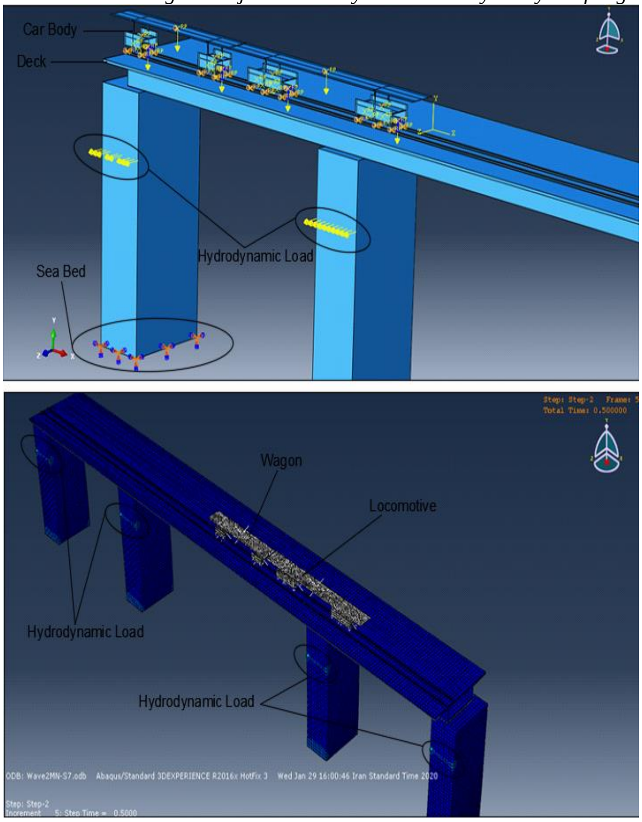


Fig 9. Train-bridge-wave (TBW) 3D model

Train-bridge-wave modeling is presented by a flowchart as shown in Fig. 10 to show the solving methodology.

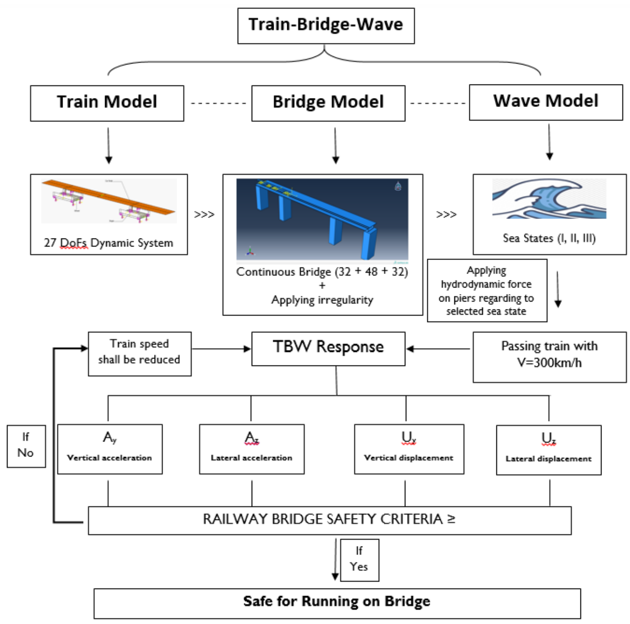


Fig 10. Train-bridge-wave-irregularity solving methodology

3.4. Model validation

The 3D finite element model of Train-Bridge-Wave was validated according to numerical simulation results of Train-Bridge model with considering 10 MN vessel collision load which is applied on pier 2 at level +10 m above the seabed. The vessel load is taken from Ref. 19 and represents the collision history by a ship, which is a wide continuous pulse with the total duration of 1.8 s, as shown in Fig. 11.

The equations of motion for the train–bridge system subjected to a collision load can be expressed as:

$$\begin{bmatrix} M_{VV} & 0 \\ 0 & M_{BB} \end{bmatrix} \begin{Bmatrix} \ddot{x}_V \\ \ddot{x}_B \end{Bmatrix} + \begin{bmatrix} C_{VV} & C_{VB} \\ C_{BV} & C_{BB} \end{bmatrix} \begin{Bmatrix} \dot{x}_V \\ \dot{x}_B \end{Bmatrix} + \begin{bmatrix} K_{VV} & K_{VB} \\ K_{BV} & K_{BB} \end{bmatrix} \begin{Bmatrix} x_V \\ x_B \end{Bmatrix} = \begin{Bmatrix} F_{VB} \\ F_{BV} \end{Bmatrix} + \begin{Bmatrix} 0 \\ F_C \end{Bmatrix} \quad (3.6)$$

Where M, C and K are mass, damping and stiffness matrices of the train–bridge system, x, $\dot{x}$ and $\ddot{x}$ are displacement, velocity and acceleration vectors, respectively; F_{VB} and F_{BV} are interaction forces between vehicle and bridge, and the subscripts V and B represent vehicle and bridge, respectively. The components of these matrices and vectors can be found in Ref. 19. F_C is the generalized vector of the collision load applied on the bridge.

In the validation stage, the train consists of wagons and locomotives with considering vessel collision load is modelled as shown in Fig. 12, and lateral acceleration time histories comparison at the top of pier 2 under vessel collision load for a train speed of 200 km/h is presented as Fig. 13. In the sensitivity analysis, the train consists of one locomotive and one wagon. The axle loads of locomotive and wagon are 19.5 and 14.25 tons, respectively. Dimensions and mechanical properties of the train car (27-DOFs dynamic system) are described in Fig. 2 and Table 3. Vessel impact is modeled as concentrated loads which are distributed on contact level of vessel and pier 2, as shown detailed in Fig. 12. Mesh size is one of the effective parameters in FEM analyses. Mesh configuration can be selected regarding to several conditions. Although smaller elements lead to a higher precision of the model, they require more time to analyze. In this research, several analyses are carried out with various mesh sizes on the bridge model to determine the optimum meshing dimensions. Results did not experience any considerable changes by decreasing the mesh sizes smaller than 0.5 m. Consequently, in this study, optimum mesh size is selected 0.5 m as shown in Fig. 12 to obtain proper train, rail and deck interactions. Moreover, choosing this mesh size is helpful about including rail and deck connection points. The comparison with numerical study demonstrated that the results of the present model were close to collision test results. The accuracy of the results of the two models is higher than 92% for maximum values and 87% for root mean square as shown in Fig. 13. These 8% and 13% differences for maximum and RMS values could be due to some of the simplifications considered in the train-bridge interaction model, input parameters and modeling errors, calculation methods and etc. In this study, time step is taken as 0.005 s. Xia et al.[18] considered this parameter as 0.0001 s in their numerical analysis. This subject is one of the main reasons for 13% difference between the results of present study and Xia et al.[18] results.

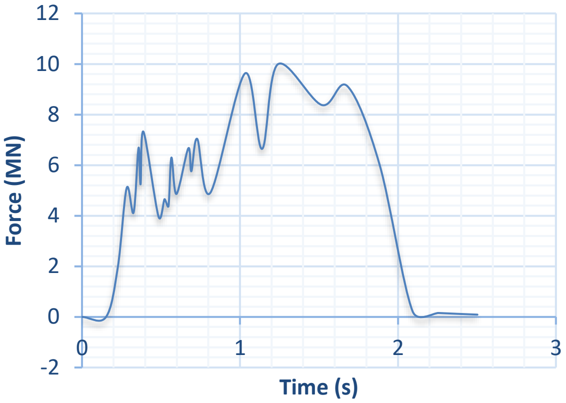


Fig 11. Time histories of vessel collision load

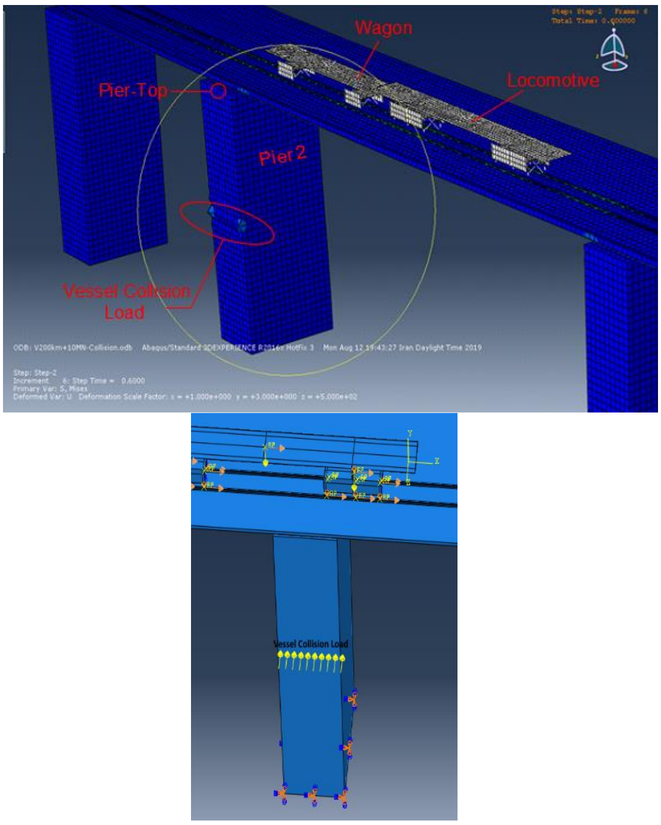


Fig 12. 3D validation model for considering vessel collision load

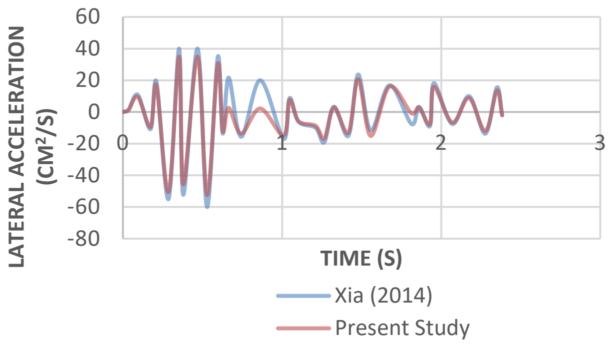


Fig 13. Comparing lateral acceleration time histories at the top of pier 2 under vessel collision load for a train speed of 200 km/h

4. Sensitivity Analyses

By using this 3D validated model, the effects of some important parameters on the running safety of high-speed train on a bridge subjected to hydrodynamic load can be assessed. In this study, eight scenarios as shown in Table 6 are applied according to assuming various conditions for sea states and track irregularity. In all cases with hydrodynamic force, the time history of the sea states are applied on piers at level +15 m above the seabed.

Table 6. Scenarios for wave and irregularity variation (V=300 km/h)

Scenario	Irregularity	Hs(m)	Ts(s)
1	NA	0	0
2	NA	4.1	8.6
3	NA	8.5	11.4
4	NA	14.8	14.3
5	Applied	0	0
6	Applied	4.1	8.6
7	Applied	8.5	11.4
8	Applied	14.8	14.3

5. Sensitivity Analyses of TBW Model under Several Conditions

This section investigates the dynamic response of bridge during the train passes with speed of 300 km/h through the bridge under several sea states by time history analyses. Structural dynamic response discussed in this study includes the lateral displacement (Uz), vertical displacement (Uy), lateral and vertical acceleration (Az, Ay) response at the middle point of span. The performance of bridge structure and train (TBW model) under different sea states is carefully discussed.

5.1. The effect of hydrodynamic load on railway bridge

First, to study the effect of the waves on the safety of the bridge to train passing, analyzes are simulated with and without hydrodynamic loads. And the bridge's behavior, such as: vertical and lateral displacements and accelerations are compared when the train passes at a speed of 300 km / h.

As shown in Fig. 14, when train is passing on bridge without hydrodynamic force (wave height=0), the amount of lateral displacement under train passing (which is less than 1 mm) is less than the permissible value. In the following, by applying hydrodynamic loads on piers and increasing the height of the wave, the lateral displacement of the deck increases and exceeds the permissible values of the European and Chinese codes.

Lateral displacement response of the bridge subjected to stormy hydrodynamic load (H = 14.8 m) could be up to 26 times higher than the ones without hydrodynamic load.

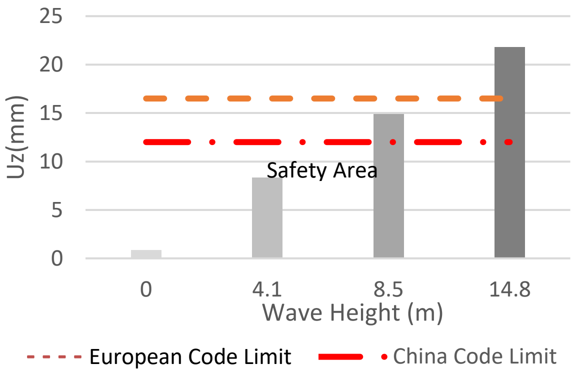


Fig 14. Lateral displacement of the bridge deck against several sea states

As shown in Fig. 15, by applying hydrodynamic loads on piers and increasing the height of the wave, the vertical displacement of the deck increases but do not exceed the permissible values of the codes. However, due to the increasing trend of displacement with increasing wave height, the displacement will be approached to critical values. (Negative value indicates downward vertical displacement)

Vertical displacement response of the bridge subjected to stormy hydrodynamic load (H = 14.8 m) is 40% higher than the ones without hydrodynamic load.

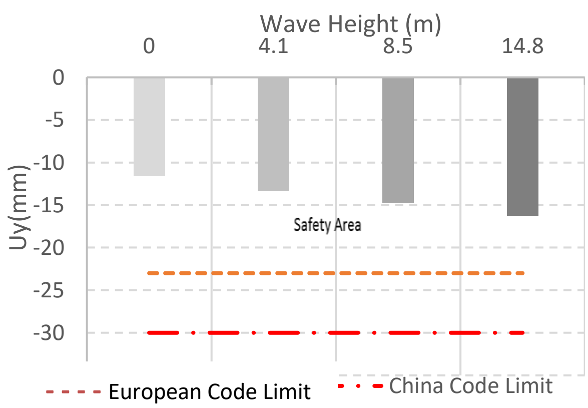


Fig 15. Vertical displacement of the bridge deck against several sea states

When train is passing on bridge without hydrodynamic force (wave height=0), the amount of lateral acceleration under train passing is less than the permissible value (which is negligible). By applying hydrodynamic loads on piers and increasing the height of the wave, the lateral acceleration of the deck increases and exceeds the permissible values of the European and Chinese codes (as shown in Fig. 16).

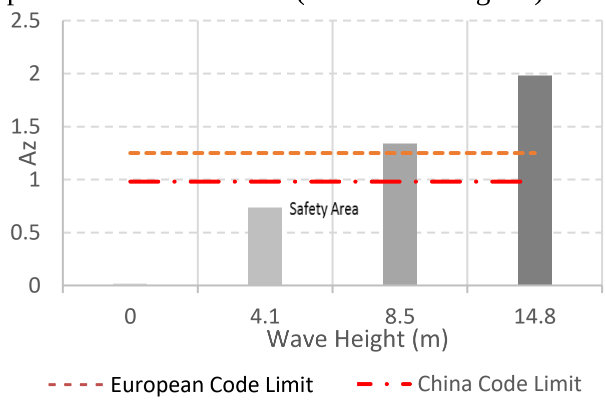


Fig 16. Lateral acceleration (m/s^2) of the bridge deck against several sea states

As shown in Fig. 17, when train is passing on bridge without hydrodynamic force (wave height=0), the amount of vertical acceleration under train passing is 0.8 m/s2, which is less than the permissible value. In the following, by applying hydrodynamic loads on piers and increasing the height of the wave, the vertical acceleration of the deck increases and exceeds the permissible values when wave height exceeds 8 m. Also, the intensity of the acceleration has increased after the 4.1-meter wave, which indicates that after this wave height, the bridge will be more sensitive to changes.

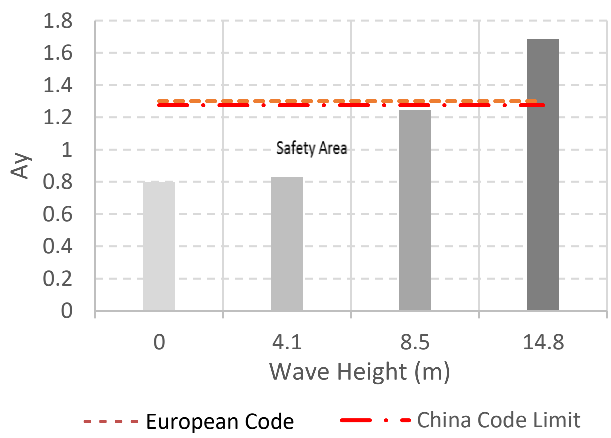


Fig 17. Vertical acceleration (m/s^2) of the bridge deck against several sea states

5.2. Effect of irregularity on TBW model

As mentioned, track irregularities are an important source of excitation for both the bridge and the vehicle. To study the effect of irregularity on TBW model and safety of the bridge to train passing, 4th quality level of

Association of American Railroads [39] is applied on TBW model (as shown in Fig 18). The bridge's behavior, such as: vertical and lateral displacements and accelerations are compared when the train passes at a speed of 300 km / h.

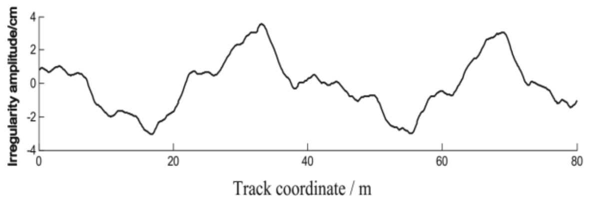


Fig 18. The track profile irregularity for line level 4[39]

As shown in Figs. 19-22, when train is passing on bridge, the amount of lateral and vertical displacements and accelerations under train passing are increased by applying track profile irregularity.

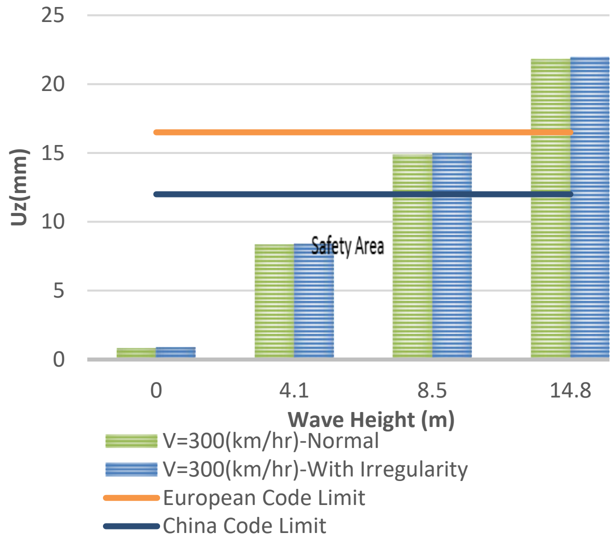


Fig 19. Lateral displacement of the bridge deck with and without irregularity against several sea states

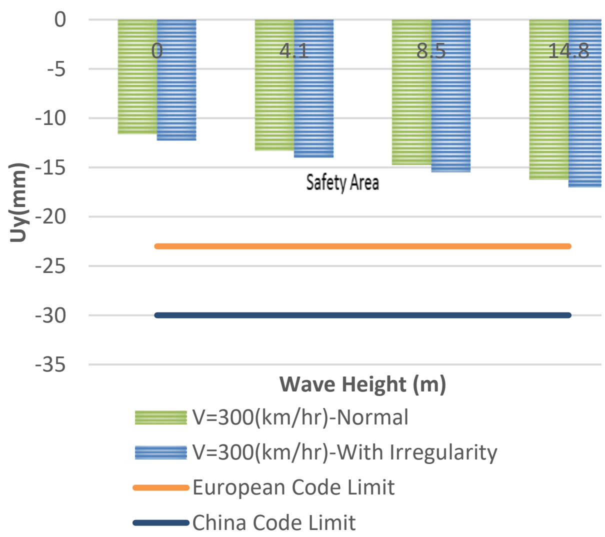


Fig 20. Vertical displacement of the bridge deck with and without irregularity against several sea states

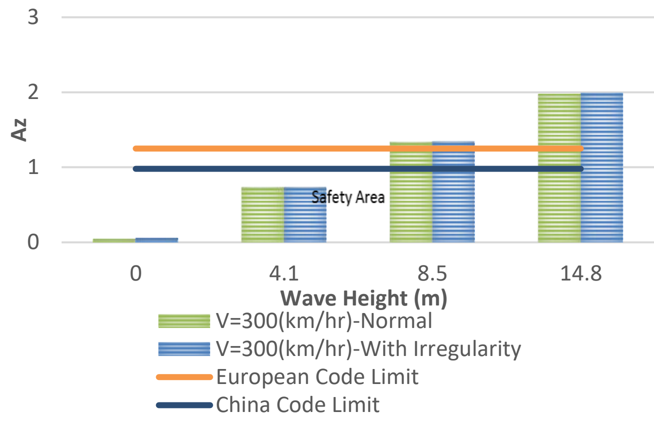


Fig 21. Lateral acceleration (m/s^2) of the bridge deck with and without irregularity against several sea states

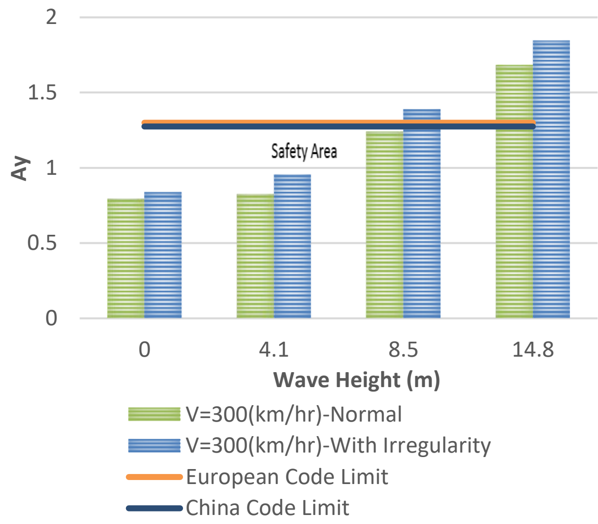


Fig 22. Vertical acceleration (m/s^2) of the bridge deck with and without irregularity against several sea states

Figs. 23-26 show variation of TBW's responses when irregularity applies on the model.

By applying irregularity on the model without hydrodynamic load (wave height=0), and train is passing on bridge, the amount of lateral acceleration increases more than 30% as shown in Fig. 23. (About 32% for RMS and 35% for maximum value)

But as shown in Figs 24-26, by applying irregularity on the model with applying hydrodynamic load (wave height=4.1, 8.5, 14.8m), variation of lateral acceleration and displacement are not increased considerable. This is because of hydrodynamic load greater impact than track irregularity in these cases.

Variation of vertical acceleration and displacement are increased considerable by applying irregularity (about 10% for acceleration and 5% for displacement). But amount of variation is decreased when hydrodynamic load is increased, as shown in Figs. 24-26.

Generally, irregularity has greater effect on vertical acceleration and displacement than horizontal ones in presence of hydrodynamic load. Combination of these two phenomena (wave and irregularity) jeopardizes the running safety of train when it is crossing the bridge.

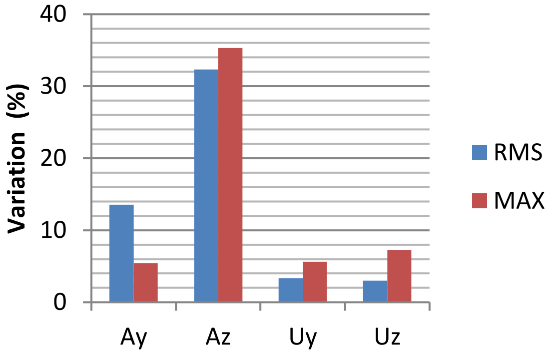


Fig 23. Variation of TBW's responses when excited by irregularity (wave height=0)

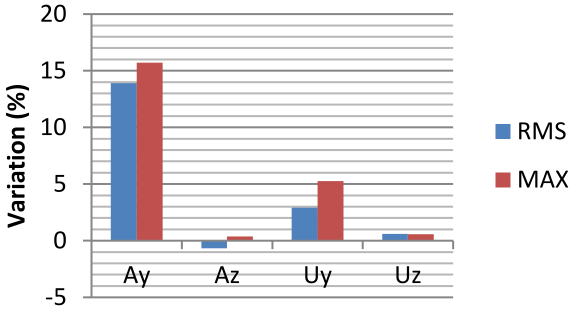


Fig 24. Variation of TBW's responses when excited by irregularity (wave height=4.1 m)

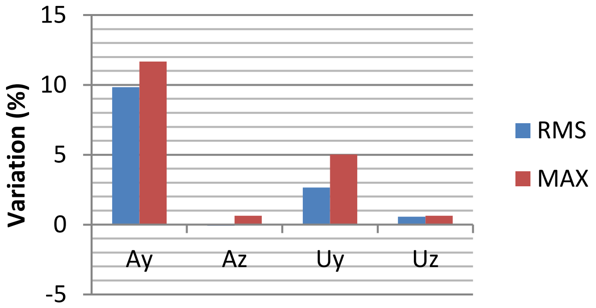


Fig 25. Variation of TBW's responses when excited by irregularity (wave height=8.5 m)

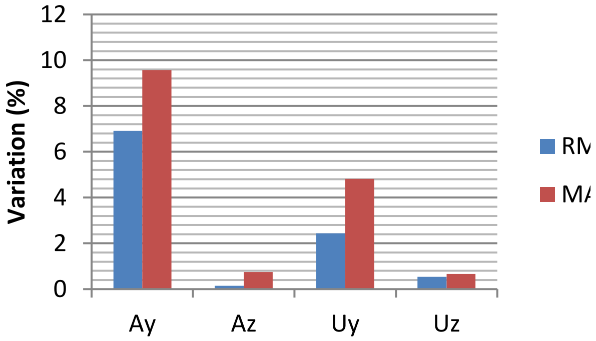


Fig 26. Variation of TBW's responses when excited by irregularity (wave height=14.8 m)

6. Conclusion

The dynamic analysis of coupled train–bridge systems subjected to hydrodynamic loads is a rather complex problem, which is related to the running speed of the train, specification of car-body, train axle loads, specification of bridge, wave height, wave periods and length, the application position and the direction of the hydrodynamic load, and many other factors.

In this study, the dynamic behavior of the 3D train–bridge system subjected to different hydrodynamic loads (TBW model) is carried out. Also additional analyses are done by applying AAR irregularity [39] to the model. By taking a continuous bridge with (32 + 48 + 32) m box girders as a case study, the dynamic responses of the bridge in mid-span of bridge which is under train passing and subjected to several hydrodynamic loads are analyzed. An assessment procedure for the running safety of high-speed train on a bridge subjected to hydrodynamic load is proposed.

The following conclusions can be drawn from sensitivity analyzes of TBW model under several sea-states and track irregularity:

(i) Hydrodynamic load has an obvious effect on the dynamic responses of the bridge. Both lateral and vertical displacements and accelerations responses of the bridge subjected to hydrodynamic load are much greater than the ones without hydrodynamic load.

(ii) Vertical displacement and acceleration responses of the bridge subjected to stormy hydrodynamic load are 40% and 100% higher than the ones without hydrodynamic load, respectively.

(iii) The lateral displacement and acceleration of the bridge are more influenced by hydrodynamic load. By applying hydrodynamic loads on piers and increasing the height of the wave, the lateral displacement and acceleration of the deck increase and exceed the permissible values of the European and Chinese codes.

(iv) Lateral displacement response of the bridge subjected to stormy hydrodynamic load could be up to 26 times higher than the ones without hydrodynamic load.

(v) Vibrations induced by hydrodynamic load have a great effect on the dynamic responses of railway bridge and train running safety. The running safety of the train is affected by both the type of sea-state and track irregularity. Strong waves may threaten the running safety of high-speed trains.

(vi) Results of TBW's sensitivity analyses have shown the importance of sea-states conditions for train safe and comfortable running.

(vii) In very stormy conditions like sea state III (H = 14.8 m), it is not safe for train running.

(viii) The effect of irregularity on the dynamic responses of the bridge is obvious. By applying irregularity on the model without hydrodynamic load (wave height=0), and train passing on bridge, the amount of lateral acceleration is increased more than 30%.

(ix) By applying irregularity to the model with hydrodynamic load, variation of lateral acceleration and displacement are not increased considerable. Because hydrodynamic load has greater impact than track irregularity in these cases.

(x) Irregularity has greater effect on vertical acceleration and displacement than horizontal ones in presence of hydrodynamic load. Combination of these two phenomena (wave and irregularity) jeopardizes the running safety of train when it is crossing the bridge.

Acknowledgment

We would also like to show our gratitude to Professor He Xia and Professor Nan Zhang from Beijing Jiao tong University for sharing their data for China High Speed Railway Bridge specifications with us during the course of this research, and we thank for their so-called insights.

7. References

[1] M. Jahangiri and J. A. Zakeri, "Dynamic analysis of train-bridge system under one-way and two-way high-speed train passing," *Struct. Eng. Mech.*, vol. 64, no. 1, pp. 33–44, 2017.

[2] C. Fang, Y. Li, K. Wei, J. Zhang, and C. Liang, "Vehicle – bridge coupling dynamic response of sea-crossing railway bridge under correlated wind and wave conditions," 2018.

[3] L. Frýba, *Dynamics of railway bridges*. Thomas Telford Publishing, 1996.

[4] X. C. Liu, B. L. Wang, L. C. Yang, and Y. Jia, "Finite Element Analysis of Pier Top Horizontal Displacement Caused by Newly-Built Road under High-Speed Railway Bridge," *Appl. Mech. Mater.*, vol. 353–356, pp. 823–827, 2013.

[5] P. Museros, M. . Romero, A. Poy, and E. Alarcon, "Advances in the analysis of short span railway bridges for high-speed lines.," *Comput. Struct.*, 2002.

[6] B. R. Ellis, T. Ji, and a. J. Bell, "Horizontal movements of frame structures induced by vertical loads," *Proc. ICE - Struct. Build.*, vol. 156, no. 2, pp. 141–150, 2003.

[7] T. Miyata and K. Yamaguchi, "Aerodynamics of wind effects on the Akashi Kaikyo Bridge," *J. Wind Eng. Ind. Aerodyn.*, vol. 48, no. 2–3, pp. 287–315, 1993.

[8] M. Yasuda, M. Kitagawa, T. Moritni, and S. Fukunaga, "Seismic Design and Behavior During the Hyogo-Ken Nanbu Earthquake of the Akashi Kaikyo Bridge," *Proc. 12th World Conf. Earthq. Eng. Auckland, New Zeal.*, vol. Paper No., pp. 3–10, 2000.

[9] R. F. da S. Dias, "Dynamic Behaviour of High Speed Railway Bridges. Vehicles Lateral Dynamic Behaviour," *Civ. Eng.*, no. November, p. 172, 2007.

[10] K.Liu, G. De Roeck, G. Lombaert, "The effect of dynamic train-bridge interaction on the bridge response during a train passage," *J. Sound Vib.*, 2009.

[11] S. Hughes, "a Critical Analyis of the Øresund Bridge , Connecting Copenhagen To Malmö," no. April, 2010.

[12] K. Bargi and A. Aghabozorgi, "Dynamic Analysis of High Speed Train Passing on Bridge," *Tehran Univ. Civ. Dep.*, 2010.

[13] J. Varandas, P. Hölscher, and M. Silva, "Dynamic behaviour of railway tracks on transition zones.," *Comput. Struct.*, 2011.

[14] S. Rashid, "Parametric study of bridge response to high speed trains," p. 104, 2011.

[15] Y. Bouassida *et al.*, *Bridge design to eurocodes*, vol. 1, no. 1. 2012.

[16] S. Melaku and H. Qiu, "Transient Dynamic Analysis of Simple Railway Bridge under Train Moving Load," pp. 106–111, 2014.

[17] C. Y. Xia, J. Q. Lei, N. Zhang, H. Xia, and G. De Roeck, "Dynamic analysis of a coupled high-speed train and bridge system subjected to collision load," *J. Sound Vib.*, vol. 331, no. 10, pp. 2334–2347, 2012.

[18] C. Y. Xia, H. Xia, and G. De Roeck, "Dynamic response of a train-bridge system under collision loads and running safety evaluation of high-speed trains," *Comput. Struct.*, vol. 140, pp. 23–38, 2014.

[19] H. Xu, Y.L., Zhang, N., Xia, "Vibration of coupled train and cable-stayed bridge systems in cross winds," *Eng. Struct.*, 2004.

[20] Y. . Li, Y., Qiang, S., Liao, H., Xu, "Dynamics of wind–rail vehicle–bridge systems," *J. Wind Eng. Ind. Aerodyn.*, 2005.

[21] N. . Alexander, "Multi-support excitation of single span bridges, using real seismic ground motion recorded at the SMART-1 array," *Comput. Struct.*, 2008.

[22] P. Montenegro e Almeida, "A Methodology for the Assessment of the Train Running Safety on

Bridges," p. 292, 2015.

[23] C. Xia, J. Ma, and H. Xia, "Dynamic analysis of a train-bridge system to vessel collision and running safety of high-speed trains," pp. 509–514, 2015.

[24] Y. Li, J. Deng, B. Wang, and C. Yu, "Running safety of trains under vessel-bridge collision," *Shock Vib.*, vol. 2015, 2015.

[25] S. M. and P. J. Ataei N, "Response sensitivity for probabilistic damage assessment of coastal bridges under surge and wave loading," *J. Transp. Res. Board*, 2010.

[26] T. Kitada, "Considerations on recent trends in, and future prospects of, steel bridge construction in Japan," *J. Constr. Steel Res.*, 2006.

[27] Y. S. Robertson IN, Riggs HR, "Lessons from hurricane Katrina storm surge on bridges and buildings," *J. Waterw. Port, Coastal, Ocean Eng.*, 2007.

[28] C. Bradner, T. Schumacher, A. M. Asce, D. Cox, C. Higgins, and M. Asce, "Experimental Setup for a Large-Scale Bridge Superstructure Model Subjected to Waves," *J. Waterw. Port, Coast. Eng.*, vol. 137, no. 1, pp. 3–11, 2011.

[29] M. Cuadrado, P. Gonzalez, J. M. Goicolea, J. Nasarre, and R. Dias, "Analysis of lateral displacements in large railway viaducts under traffic loads. Impact on ride safety and passenger comfort," *Proc. 8th World Congr. Railw. Res.*, pp. 1–12, 2008.

[30] S. Chakrabarti, "Discussion of nondeterministic analysis of offshore structures.," *J. Eng. Mech.*, 1971.

[31] R. M. Sorensen, *Basic Wave Mechanics for Ocean Engineering*. New York: John Wiley, 1993.

[32] P. B. Song, "Study on the calculation method for hydrodynamic pressure of bridge piers in deep water under earthquakes University of Science and Technology Beijing main contents," 2010.

[33] H. Karadeniz, "Spectral analysis of offshore structures under combined wave and earthquake loadings," *Proc. 1999 Ninth Int. Offshore Polar Eng. Conf. (Volume 4), Brest, Fr. 30 May - 4 June 1999*, vol. IV, pp. 504–511, 1999.

[34] S. Yim, "Modeling and simulation of tsunami and storm surge hydrodynamic loads on coastal bridge structures," *21st US Japan Bridg. Eng. Work.*, no. April, pp. 1–14, 2005.

[35] Indian Institute of Technology, *IITK-RDSO GUIDELINES ON SEISMIC DESIGN OF RAILWAY BRIDGES*, no. November. 2010.

[36] H. Xia and N. Zhang, "Dynamic analysis of railway bridge under high-speed trains," *Comput. Struct.*, vol. 83, no. 23–24, pp. 1891–1901, 2005.

[37] Christopher W Jenks, "Rail Corrugation Mitigation in Transit," *Transit Coop. Res. Progr. Spons. by Fed. Transit Adm.*, 1998.

[38] S. L. Grassie, "Rail corrugation : characteristics , causes , and treatments," pp. 1–17, 2009.

[39] X. Lei, *High speed railway track dynamics. Models, Algorithms and Applications*. Science Press, Beijing/Springer Nature Singapore Pte. Ltd., 2017.

[40] CEN, *EN 1990-Eurocode - Basis of Structural Design*. 2005.

[41] CEN, *EN 1991- Eurocode: Actions on Structures*. 2005.

[42] CEN, *EN 1998- General Rules, Seismic Actions and Rules for Buildings*. 2005.

[43] B. G. Jeon, N. S. Kim, and S. Il Kim, "Estimation of the vibration serviceability deflection limit of a high-speed railway bridge considering the bridge-train interaction and travel speed," *KSCE J. Civ. Eng.*, vol. 20, no. 2, pp. 747–761, 2016.

[44] *Code for Design of High-Speed Railway (China)*. Ministry of Railways of the People's Republic of China, 2009.

[45] ISO, *ISO 2631- Mechanical Vibration and Shock- Evaluation of Human Exposure to Whole-Body Vibration*. 2002.

[46] Y. Jiang, B. K. Chen, and C. Thompson, "A comparison study of ride comfort indices between Sperling's method and EN 12299," *Int. J. Rail Transp.*, vol. 7, no. 4, pp. 279–296, 2019.

[47] G. Bhaskar, A., Johnson, K.L., Wood, G.D. and Woodhouse, "Wheel-rail dynamics with closely conformal contact, Part 1: dynamic modelling and stability analysis," *Instn. Mech. Eng.*, 1997.

[48] A. Razzaghi Kalajahi, M. Esmaeili, and J. A. Zakeri, “DYNAMIC ANALYSIS OF A COUPLED HIGH-SPEED TRAIN AND BRIDGE SYSTEM SUBJECTED TO SEA WAVE HYDRODYNAMIC LOAD,” *Lat. Am. J. Solids Struct.*, vol. 18, no. 1, pp. 1–21, 2020.

[49] H. J. Cao, F. Yi, and W. B. Feng, “Estimate of the extreme wave height in the South China Sea using GPD method,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 189, no. 5, 2018.