NASS NAN YANG ACADEMY OF SCIENCES

Sustainable Marine Structures

https://ojs.nassg.org/index.php/sms

SHORT COMMUNICATION

Functionally Graded Material and Its Application to Marine Structures

Chandrasekaran, S.[1*] **Hari, S.**[2]

1. Department of Ocean Engineering., IIT Madras, Chennai, India
2. School of Petroleum Technology, Pandit Deendayal Petroleum University, Gandhinagar, India

ARTICLE INFO

Article history

Received: 14 February 2022

Accepted: 21 February 2022

Published Online: 28 February 2022

Keywords:

Marine structures

Functionally graded materials

Marine riser

Offshore structures

Form-dominant design

ABSTRACT

Marine structures are exposed to harsh weather conditions, demanding special pre-requisites in design and functional perspectives. Under dynamic loads of larger magnitude, the material-centric design procedure alone is not feasible to ensure the safe disbursement of loads. The compliant offshore structures resist loads primarily by their geometric novelty, and hence their design is form-dominant and no more strength (material) dominant. Large displacements in the rigid body modes in the horizontal plane under lateral loads require their construction material to possess enough ductility to absorb this energy. Steel is one of the most competitive materials for marine structures as it offers good ductility, but corrosion in the marine environment is a major concern. It undergoes strength and functional degradations and therefore requires serious investigation. In the present study, functionally graded material (FGM) is proposed to substitute for steel in marine applications. The method of fabricating FGM and assessing its mechanical and durability properties are discussed. Results show that FGM possesses strength and durability properties at par with the conventionally used X52 steel for marine risers. The presented study will be a major initiative towards future research in exploring competent materials which will be strong and sustainable in the marine environment.

1. Form-dominant Design Approach

Offshore structures are intended to perform oil and gas exploration under the marine environment while facing many challenges in extreme load combinations, sustainability against the corrosive environment, and a quick return on investment (RoI) [1,2]. The exploration activities towards ultradeep water and arctic regions induced a paradigm shift in their design procedures [3]. Advances in technology and industry maturity make deep-water oil and gas exploration an attractive investment. Furthermore, wind and wave energy have become the recent focus and pivotal points of attraction for green energy harvest. Environmental loads that arise from

*Corresponding Author:

Chandrasekaran, S.,

Department of Ocean Engineering., IIT Madras, Chennai, India;

Email: drsekaran@iitma.c.in

DOI: http://dx.doi.org/10.36956/sms.v4i1.490

waves, wind, and current become more severe in ultra-deepwater. Offshore engineers are increasingly deploying compliant systems that are permitted to undergo large displacements. For example, exploratory and production drilling has become more comprehensive with the recent developments in the design of semi-submersibles [4]. Effective design methods, based on the postulated failure analyses help arrive at the safer and sustainable design of platforms for extreme ocean conditions. The natural periods and damping ratios for the Semi-submersible at 1500 m and 2000 m water depths, with and without a submerged buoy, are obtained from free-oscillation tests; results are shown in Table [5]. It is seen that considerable periods in the surge, sway indicate higher flexibility about the horizontal plane. In contrast, small periods in roll, pitch, and heave show that they are stiff in the vertical plane. By this compliant approach in the design, natural periods in sway and yaw are found to be increased, along with a significant increase in the damping ratios for the surge, pitch, and yaw in the presence of a submerged buoy. It is interesting to note that a semi-submersible platform is usually characterized by possessing free modes, indicating that the natural periods in all degrees of freedom are above the wave periods [6]. Postulated failure analysis for compliant platforms helps investigate the failure modes under extreme conditions to assess their survivability. Surge response is significantly higher in the case of postulated failure of mooring lines. Addition of buoy at an appropriate location in the mooring help to reduce the response of mooring lines [4]. Surge response, which is the controlling factor for design is significant in the absence of submerged buoys.

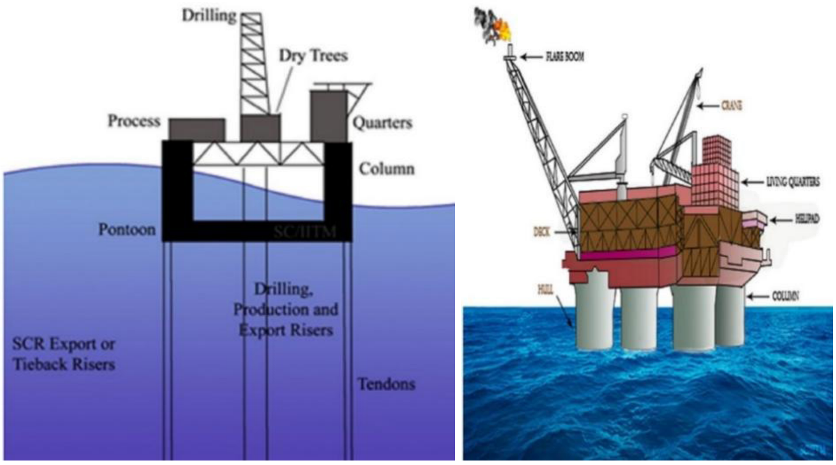
Compliant offshore platforms are designed to resist lateral loads from waves, current and wind by their innovative geometric form. See, for example, Tension Leg Platform (TLP), Spar, Triceratops, and semi-submersibles. Out of the six degrees of freedom exercised by the rigid body motion of these platforms, two translational and one rotational degree, namely surge, sway, and yaw, are very flexible, exhibiting considerable periods. It makes the platform flexible in the horizontal plane and enables it to resist the lateral loads by undergoing large displacements. The remaining degrees of freedom, namely heave (translational in Z-axis) and roll and pitch (rotational), exhibit very stiff behaviour and make the platform rigid in the vertical plane. Such hybrid motion characteristics are salient features of compliant platforms. Let us consider a TLP, whose conceptual figure is shown in Figure 1; a figure of Neptune TLP shown by the side gives an idea of various structural components. It consists of vertical columns and pontoons designed as tubular members to enhance buoyancy. As the design concept conforms to the fact that buoyancy shall exceed the weight of the platform, it is position-restrained by tethers, which are under axial pretension to balance the excessive buoyant force. As a result, motion on the vertical plane such as heave, pitch and roll are restrained while it allows large displacements along with surge, sway and yaw degrees-of-freedom.

Table 1. Dynamic characteristics of moored Semisubmersible [5]

Description			Surge	Sway	Heave	Roll	Pitch	Yaw
Without buoy	1500 m water depth	Tn (s)	209	165	21	24	25	49
		ζ (%)	6.15	6.92	2.47	2.97	0.93	6.51
	2000 m water depth	Tn (s)	193	184	25	25	25	54
		ζ (%)	5.84	6.38	4.15	4.75	1.91	7.98
With buoy	1500 m water depth	Tn (s)	195	183	21	23	24	54
		ζ (%)	6.56	6.77	1.20	1.44	1.32	10.36
	2000 m water depth	Tn (s)	213	199	21	23	24	53
		ζ (%)	6.87	6.21	1.45	1.06	0.83	4.61

As seen in Figure 2 [7], which illustrates the TLP mechanics, a strong coupling is seen between surge (offset) and heave (set down) motion. Large displacements along surge invoke a supportive resistance from heave motion, which helps to encounter the lateral loads. This form-dominance characteristic makes their design unique, imparting a design shift from material strength-dominant to form-dominant. In addition, the horizontal components of the increased tension in the tethers help the platform return to its equilibrium position under the presence of loads. It is referred to as recentering, and geometric stability is imposed by the recentering ability taught in the design. Another classic example is the triceratops, shown in Figure 3 [7]. Offshore triceratops is a new generation of offshore platforms that are intended for use in ultra-deep waters. The deck of the platform is supported by the buoyant legs, which are, in turn, anchored to the seabed using pre-tensioned tethers. Ball joints are placed between the deck and the buoyant legs (please, see Figure 3), which partially isolate the deck from the buoyant legs and help counteract the lateral loads and moments [8]. These ball joints transfer only the translations from the legs to the deck and vice-versa; they restrain the moment's transfer and thus partially isolate the deck from the buoyant legs. Such design methods are often referred to as FORM-dominant design, which forms the basis for most of the compliant offshore structures.

Large displacements of such compliant structures demand a ductile material to absorb these motions without



a) conceptual figure b) Neptune TLP [3]

Figure 1. Offshore Tension Leg Platform

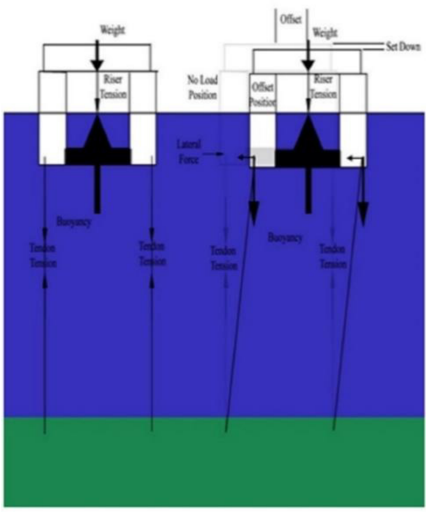


Figure 2. TLP mechanics

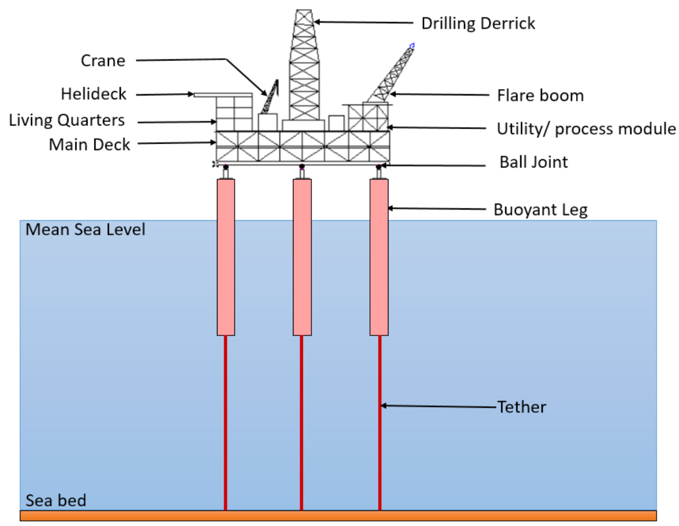


Figure 3. Offshore Triceratops

any strength degradation [1,2]. Although steel is recognised as the most suitable material, it corrodes in the marine environment. Hence, in addition to the desired strength requirements, materials for marine structures should also possess desirable functional requirements for their sustainability in the marine environment. A few of them are namely corrosion-resistance, anti-biofouling, and non-toxic. No single material can meet all such challenges of functionally and structurally excellent. Furthermore, even if such materials are manufactured, they cannot be used to construct marine structures unless the design codes of practices recommend them. Therefore, the current trend is to address the design by strength considerations and fulfil others using chemical or biological treatments. As a result, the sustainability of marine structures encounters a bi-fold problem: one concerning strength degradation and the other is the functional degradation under ageing. This challenge faced by the marine structures during their service life needs to be addressed to make them sustainable and functional.

2. Functionally Graded Material

Functionally graded materials (FGM) are useful in the Defence, aerospace, and medical field; recent attempts are made to assess their use in the marine environment [9]. Process industries where pipelines are subjected to corrosion under chlorides and sulphides, many mechanical components and appurtenances are replaced with FGM [10]. FGM is a novel material manufactured by functionally-grading two metal components, which are chosen based on strength and corrosion resistance. Manufacturing such materials is a big challenge as the manufacturing process shall impose significant challenges in achieving the desired properties of FGM [11]. In the manufacturing process of FGM, materials of desired characteristics are chosen, and their geometric compositions (not the metallurgical composition), in terms of thickness and number of layers, are varied continuously across the cross-section. Thus, the composition and microstructure are altered along the cross-section to generate the desired property gradient. It is intended to utilise completely the mechanical, metallurgical and structural properties of the original materials while forming the FGM [12]. The wire arc additive manufacturing method (WAAM) enables the metallurgical composition of user-defined materials by a step-wise addition [13]. The component metals are deposited in layers in wires, while an electric arc is used as the heat source. Metallic wires are advanced using a secondary wire-feeder at the desired speed. A high-pulse current is supplied to form an arc between the electrode wires and the substrate, resulting in the melting of the filler tip of these advancing wires. A stainless-steel substrate is used to deposit the materials, while a high-power source is used for the deposition process. Figure 4 shows various components of the WAAM unit, namely the Cold Metal Transfer (CMT) torch, the substrate and the CNC machine integrated with the torch. The deposition parameters for the WAAM process are based on the constituent materials and the appropriate fillers.

Marine risers are subjected to severe corrosion in the presence of hydrogen sulphide and chlorides. Further, stress corrosion is accelerated due to the high-pressure and high-temperature conditions [14]. Hence, marine risers are a classic example of structural members under stress concentration and corrosion. X-52 steel is a common candidate for marine risers. In the present study, X-52 carbon-manganese steel is graded with duplex stainless steel to manufacture FGM on the lab scale. The chosen materials are code compliant for marine structures [15,16]. While duplex stainless steel possesses a higher corrosion resistance in acidic conditions, X-52 steel is a good strength contributor. As discussed in the earlier section, materials for FGM are chosen based on the functional requirements, namely strength and corrosion resistance.

Figure 5 shows the cross-section of the riser under investigation, where the inner layer of 3 mm is duplex stainless steel, and the rest of 14 mm is carbon manganese steel. The sizing of the riser is as per the existing riser of Auger TLP [17]. X-ray computed Tomography test on the FGM build confirmed that it is free from porosity and micro-cracks. FGM build, extracted from the manufactured specimen, is shown in Figure 6, where the optical markers are made to assess the longitudinal and lateral strain during the tension test. It is important to note that loading is applied parallel to the interface of the materials to observe its behaviour at the critical interface (Please see, Figure 7).

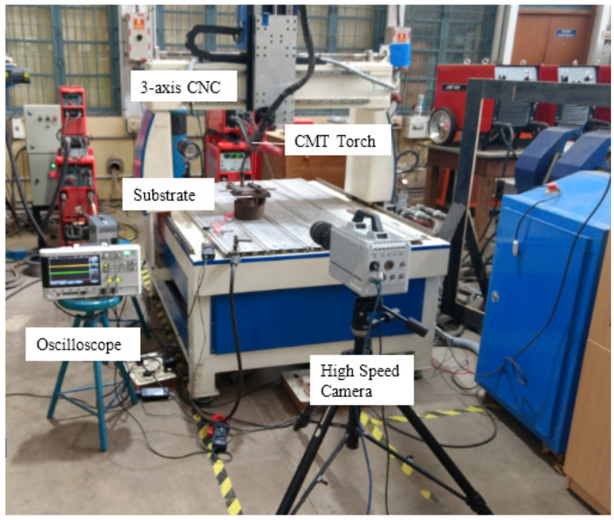


Figure 4. WAAM unit used to manufacture FGM.

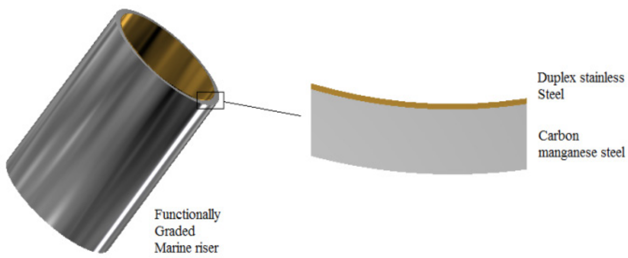


Figure 5. Cross-section of riser under investigation

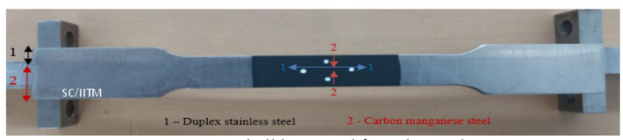
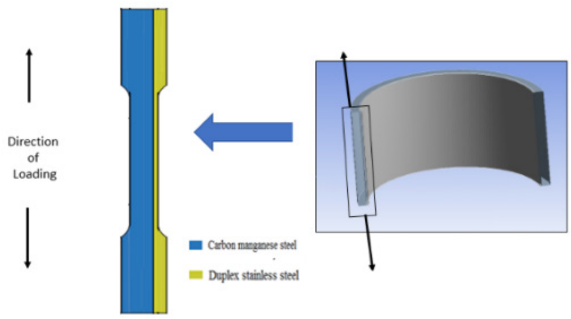
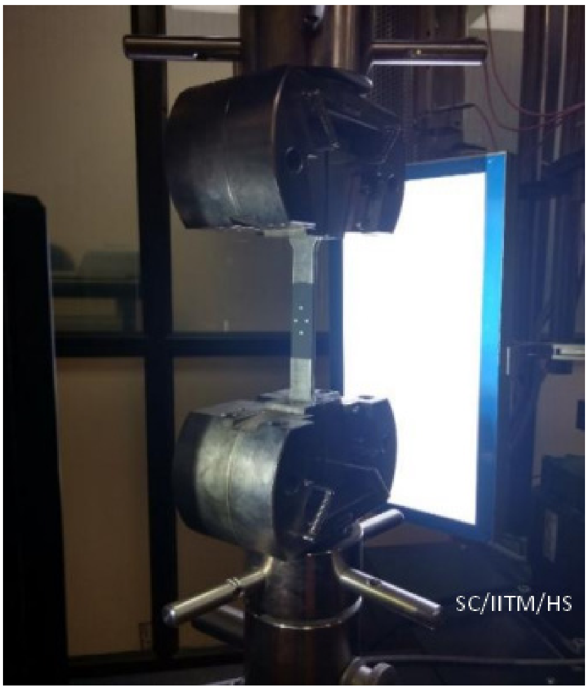


Figure 6. FGM build extracted from the specimen.

The tension tests are carried out on the FGM specimens at a strain rate of $1x10^{-3}$ s^{-1}. The ultimate strength of FGM samples is about 600 MPa, while the yield strength is about 400 MPa, with the modulus of elasticity computed as 213 GPa. Compared with X-52 steel, one can observe a significant increase in the ultimate and yield strength with a very high ductility ratio. Results are summarised in Table 2. As seen in Figure 9, the fractured sample confirms that the failure is not along with the interface of the constituent metals but similar to structural grade steel.



a) load direction

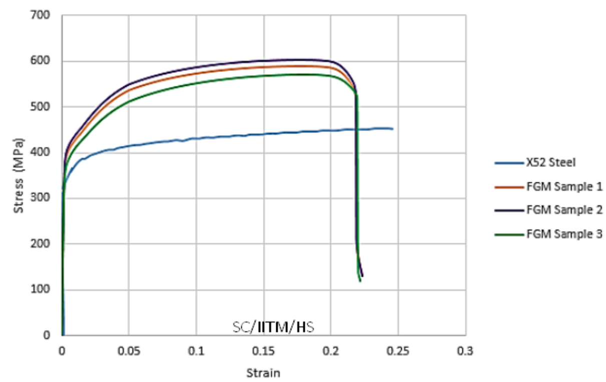


b) loaded specimen

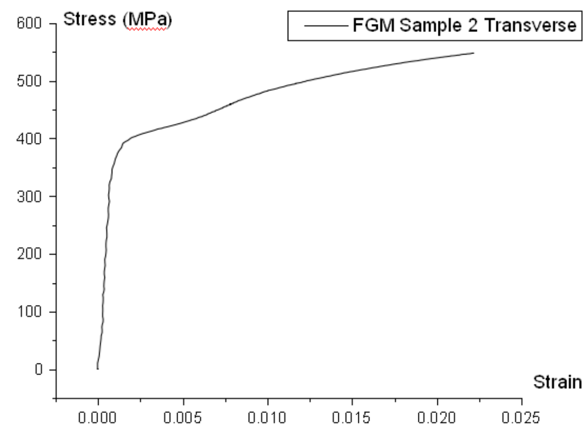
c) fractured specimen

Figure 7. Tension test

At the interface of the constituent metals, an elemental line energy dispersive X-ray analysis (EDX) is carried out to determine the chromium variation along with the interface. Figure 9 shows the EDX image, which verifies that the chromium content in duplex stainless steel is about 22% at 35 microns from the interface, and it is closer to the duplex stainless steel side. It offers corrosion resistance to FGM. X-ray diffraction analysis (XRD) resulted in an output confirming a prominent peak of (Cr 0.1, Fe 1.9) indicating the presence of chromium oxide at the interface regions.



a) longitudinal direction



b) lateral direction

Figure 8. Stress-strain relationship of FGM

Table 2. Mechanical properties of FGM builds

Material/Parameters	X52Marine Riser Steel	FGM
Youngs Modulus (GPa)	210	209.66 ± 4.48
Yield Strength (MPa)	358	390.66 ± 12.23
Ultimate Strength (MPa)	453	587.66 ±12.76
Strength Ratio	1.265	1.50 ± 0.02
Ductility Ratio	32.207	45.47 ± 0.82
Tensile Toughness (J/m3)	104.92	120.50 ± 2.84
Poisson`s Ratio	0.3	0.30 ± 0.07
% Elongation	21	22.31± 0.11

Variation in micro-hardness along the build is assessed using the Vickers Hardness test. Figure 10 shows the result, which confirms that hardness is in the range of (307-320) at the interface. A pitting corrosion test showed about twelve times more corrosion in X52 steel than the proposed FGM.

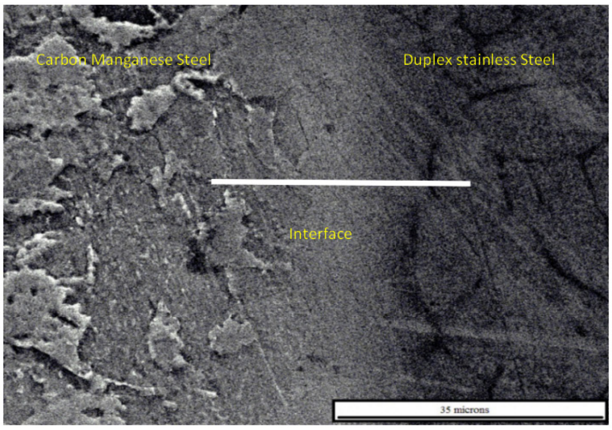


Figure 9. EDX image at the interface of FGM mould

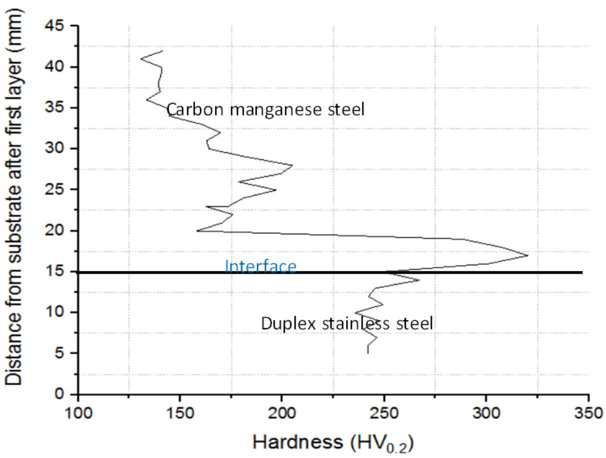


Figure 10. Micro-hardness variation in FGM build

3. Conclusions

Materials for the construction of marine structures should complement the form-dominance criteria and the strength and functional requirements to sustain the ocean environment hazards. While the design procedures are shifted to a form-centric approach, properties in materials need to be upgraded in parallel. The presented study illustrated the fabrication of FGM and its application to marine structures.More details can be seen in the detailed studies carried out by the authors [10,12]. It is seen that FGM possesses a higher yield and ultimate strength in comparison to the steel currently deployed for marine construction. In addition, it also offers excellent corrosion resistance, which was not satisfactory in the former. Significant enhancement in ductility guarantees its complementary support to large displacement characteristics of compliant marine structures. Rigorous studies on similar lines would suffice a stronger inclination for the design codes to recommend FGM as a structural material shortly.

References

[1] Chandrasekaran, S., Arvind Kr. Jain, Nasir Shafiq, M., et al., 2021. Design aids for offshore platforms under special loads, CRC press, Florida. pp. 280, ISBN: 9781032136844.

[2] Chandrasekaran, S., Nagavinothini, R., 2020, Offshore compliant platforms: Analysis, design and experimental studies, Wiley, U.K, ISBN: 978-1-119-66977-7.

[3] Chandrasekaran, S., 2019. Advanced steel design of structures, CRC press, Florida, ISBN: 978-036-72-3290-0.

[4] Chandrasekaran, S., 2020. Offshore Semi-Submersible Platform Engineering, CRC Press, Florida. pp. 240, ISBN: 978-0367673307.

[5] Chandrasekaran, S., Syed Azeem Uddin, 2020. Dynamic analysis of semi-submersible under postulated failure of restraining system with the buoy, Intl. J. of Steel Structures. 21(1), 118-131.

[6] DNV-RP-F205, 2010. Global Performance Analysis of Deepwater Floating Structures.

[7] Chandrasekaran, S., Nagavinothini, R., 2020. Parametric studies on the impact response of offshore triceratops in ultra-deep waters, Structure and Infrastructure Engineering. 16(7), 1002-1018.

[8] Chandrasekaran, S., Nagavinothini, R., 2020. Offshore triceratops under impact forces in ultra-deep arctic waters, Int. J. of Steel structures. 20(2), 464-479.

[9] Albino, J.C.R., Almeida, C.A., Menezes, I.F.M., et al., 2018. Co-rotational 3D beam element for nonlinear dynamic analysis of risers manufactured with functionally graded materials (FGM), Engineering Structures. 173, 283-299.

[10] Chandrasekaran, S., 2020. Design of Marine Risers with Functionally Graded Materials, Woodhead Publishing, Elsevier. pp. 200, ISBN: 978-0128235379.

[11] Chen, X., Li, J., Cheng, X., et al., 2017. Microstructure and mechanical properties of the austenitic stainless steel 316L fabricated by gas metal arc additive manufacturing, Mat. Sc. and Engg.,: A. 703, 567-577.

[12] Chandrasekaran, S., Hari, S., Murugaiyan, A., 2020. Wire arc additive manufacturing of functionally graded material for marine risers, J. Mat. Sc., & Engg. A. 792, 139530.

[13] Martina, F., Mehnen, J., Williams, S.W., et al., 2012. Investigation of the benefits of plasma deposition for the additive layer manufacture of Ti–6Al–4V, J. Mat.

Processing Tech. 212(6), 13.

[14] Shen, Y., Jukes, P., 2015. Technical challenges of unbonded flexible risers in HPHT and deep-water operations, Proc. of Twenty-fifth Int. Offshore and Polar Engg. Conf., June 21-26, Hawaii, USA.

[15] DNV, G., 2018. *DNVGL-RP-F112 Duplex Stainless Steel – Design against hydrogen-induced stress cracking*, DNV GL, 1-44.

[16] DNV, G., 2012. *DNV-OS-F101 Submarine pipeline systems*, Oslo: DNV GL, 1-367.

[17] Phifer, E.H., Kopp, F., Swanson, R.C., et al., 1994. Design and installation of auger steel catenary risers, Proc. of Offshore Technology Conference, 2-5 May, Houston.