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Parametric study for suggestion of the design procedure for offshore plant helideck subjected to impact load

Doo-Hwan Park[1], Jeong-Hyeon Kim[1], Yong-Jun Park[2], Jun-Hwan Jeon[3], Myung-Hyun Kim[1] and Jae-Myung Lee*[1]

[1]*Department of Naval Architecture and Ocean Engineering, Pusan National University, Busan 609-735, Republic of Korea*
[2]*Shipbuilding Division, Hyundai Heavy Industries, Co., Ltd., Ulsan 682-792, Republic of Korea*
[3]*Marine Research Institutes, Samsung Heavy Industries, Co., Ltd., Sungnam 463-400, Republic of Korea*

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Abstract. Helidecks are vital structures that act as a last exit in an emergency. They transport people and goods to and from ships and offshore plants. When designing the structure of a helideck, it is necessary to comply with loading conditions and design parameters specified in existing professional design standards and regulations. In the present study, finite element analysis (FEA) was conducted with regard to a steel helideck mounted on the upper deck of a ship considering the emergency landing of the helicopter. The superstructure and substructure were designed, and the influence of various design parameters was analyzed on the basis of the FEA results.

Keywords: helideck; offshore structure; structural design; parametric study; finite element analysis

1. Introduction

The increasing price of crude oil has led to significant demand for ship and offshore structures to develop subsea resources. Because offshore structures are operated away from land and shallow seawater, it is necessary to regularly conduct a proper dissemination of goods and people. In particular, transportation is inevitably required because offshore plants, such as floating, production, storage, and offloading vessels (FPSOs); jacket structures; and spar buoys, should be installed in a single location for several years. Helicopters have been the main method of transporting personnel to and from offshore installations for more than 60 years. In this regard, helidecks, which are platforms on which helicopters may take off and land, are essential structures installed in offshore plants. Additionally, in offshore plants, it is necessary for helicopters to act as a last exit in the occurrence of devastating offshore accidents, such as fires or explosions.

To create a structural design for a helideck, related concerns should be considered to allow the helideck to withstand severe loading scenarios that may affect the offshore structure. However, the structural requirements of a classification society for helideck design have been adhered to on the basis of previous experience without specifically considering certain varied loading conditions. In

*Corresponding author, Professor, E-mail: jaemlee@pusan.ac.kr

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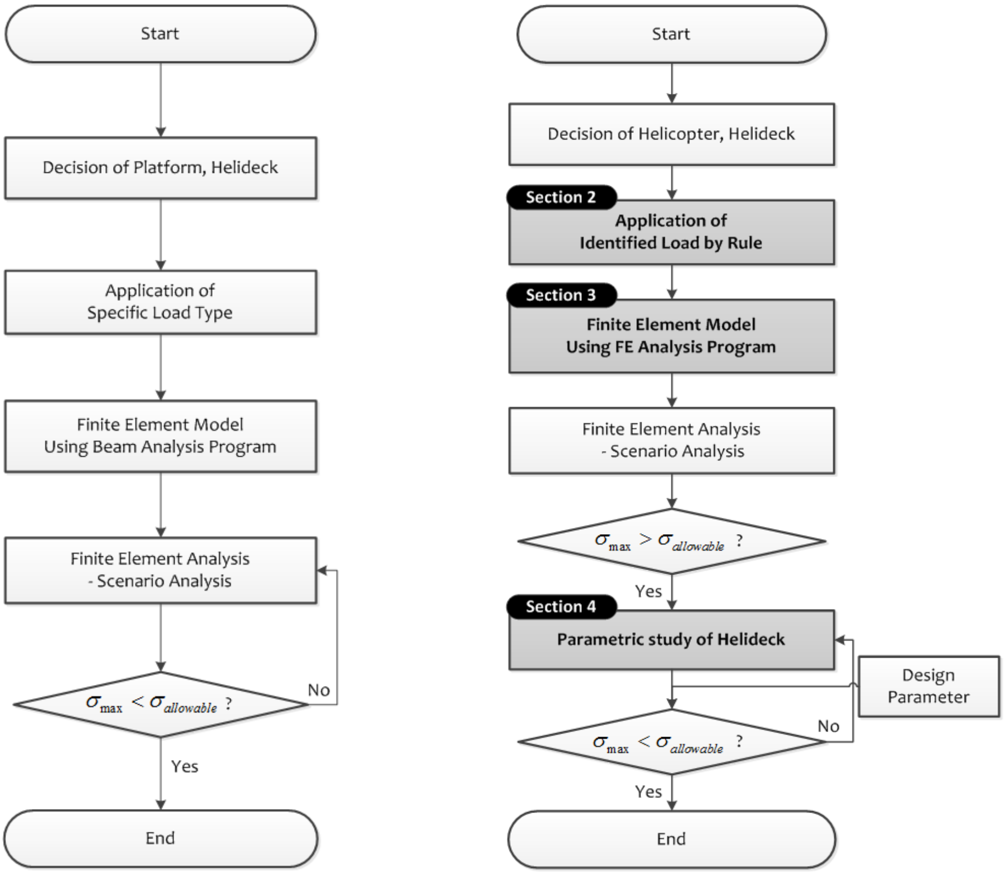


(a) (b)

Fig. 1 (a) Conventional and (b) proposed helideck design procedure

addition, although many helideck installations were constructed on ships and offshore structures in past decades, there has been little research on helideck design procedures and the parameters that affect the structural response of the helideck (Bisangi 2002, McCarthy and Wiggenraad 2001). For this reason, it is difficult to develop a new helideck design because of the lack of clarity in defining a standard safety assessment. In addition, the owners and operators of ships and offshore structures may be uncertain about whether the helideck can maintain adequate structural strength to withstand the static and dynamic loading conditions caused by the helicopter landing.

In past decades, some research has been conducted on offshore platforms and helidecks concerning their strength and suitability to withstand the landing load of a helicopter. Lee and Chung carried out a structural analysis of the planks and substructure of an aluminum helideck under the landing force of a helicopter using ANSYS as a basic step to substitute the foreign design and material, and a new plank design was devised on the basis of the analysis results (Lee and Chung 2002). Abdel Raheem conducted a nonlinear structural analysis of a fixed offshore platform for an economic and reliable design using the program SAP2000, which is similar to SACS. The numerical results and mode shapes of the system were investigated under various combinations of wave loading conditions (Abdel Raheem 2013). Vaghefi, Bagheri *et al*. used

SACS to conduct a nonlinear static analysis of a helicopter under emergency landing conditions. The structural response of the helideck was investigated specifically with regard to various landing positions, orientations, and angles (Vaghefi, Bagheri *et al*. 2013). Xu, Si *et al*. performed experiment and FEA of helideck which is made of aluminum alloy sandwich panel under static load. According to the results of the test and the finite element simulation, the mechanical properties and the deformation characteristics of the aluminum alloy deck are analyzed contrastively (Xu, Si *et al*. 2014).

In addition, some previous research outcomes concerning the helicopter landing and collision mechanisms were well presented through finite element analysis (FEA) utilizing existing analytical techniques based on actual crash and drop tests. However, such studies focused on the response of the helicopter rather than the helideck (Rashid, Place *et al*. 2015, Yonebayashi and Collins 2015, Nascimento, Majumdar *et al.* 2014, Wanhill, Symonds *et al.* 2013, Hughes, Campbell *et al*. 2008, Compos, Quintero *et al*. 2008). Although many researchers have focused on the offshore helideck, the turbulence assessments have been preferred. Park, Kim *et al*. (2015) investigated turbulence assessment methods for the offshore helideck based on the criteria suggested by CAP 437 and NORSOK C-004. Furthermore, Mentzoni, Ertesvag *et al*. (2015) simulated turbulent flow over an offshore oil-rig helideck in Norwegian by a commercial engineering CFD code with nine different turbulence models. Another relevant study is Mentzoni and Ertesvag (2015) who reviewed and discussed turbulence criteria for CFD of helideck flows in the Norwegian Norsok.

Fig. 1(a) shows the design procedure of previous studies that focused on the response of the helideck structure. As indicated in this figure, these studies considered only specific loading scenarios, such as emergency or wave loading, although numerous other landing scenarios exist. In addition, analysis was performed through helideck modeling using simple beam structures without considering the deformation of the plate or beam cross section.

Therefore, the present investigation proposes an improved design procedure to overcome the limitations of previous studies, as indicated in Fig. 1(b). Several additional scenarios are considered while sustaining the basic framework of the previous analytical process. First, the loading conditions applied to the helideck are estimated using existing professional design standards. In addition, FEA using two-dimensional (2D) elements was conducted targeting a steel helideck installed on the upper deck of a vessel (shuttle tanker) under the defined design loading conditions, and the safety of the basic helideck was evaluated. Finally, a parametric study on an existing helideck structure was performed by applying a variety of design parameters and the specific dimensions of each member. Through this, the structural response of the helideck with respect to variation in the design parameters is investigated by introducing some noted items for helideck design. In addition, each process mentioned above is performed using the improved design procedure proposed in the present study (Fig. 1(b)). The results of the present study can be utilized in the future as reference data to investigate the structural response of a helideck and confirm correlation among the design parameters.

2. Load calculations

To predict the precise structural response of the helideck, loading conditions affecting the helideck, including the landing load, self-weight, and inertial force caused by the movement of the ship, must be clearly defined. Therefore, the design and combined loading conditions subjected to

Table 1 Helideck loading specifications - Helicopter landing (HSE 2001)

Authority	ISO	CAP	HSE	ABS	BV	DNV	GL	LRS
Self-weight	-	1.5M	1.5M	-	1.5M	-	-	-
Emergency Landing	2.5M	2.5M	2.5M	1.5M	3.0M	2.0M	1.5M	1.5M 2.5M
Deck Response Factor	1.3	1.3	1.3	-	-	-	-	-
Super-imposed Load (kN/m2)	0.5	0.5	0.5	2.0	2.0	Normal class	0.5	0.2
Lateral Load	0.5M	0.5M	0.5M	-	-	0.4M	-	0.5M

Table 2 Parameters for various loads acting on the helideck structure (Park 2014)

Load type		Weight (kN)	Remark
Landing load	Normal	+62.9	*x*, *y* direction
		-245.5	*z* direction
	Emergency	+62.9	*x*, *y* direction
		-409.2	*z* direction
Self weight	Equipment	-248.0	Net×1.2 (Contingency factor applied)
	Safety net	-71.0	
	Gutter	-59.0	
	Ramp	-14.0	
	Live load	-170.0	changeable load (0.5kN/m^2)
Inertia force		+205.0	a_x=2.28 m/s^2
		+803.0	a_y=8.95 m/s^2
		+579.0	a_z=6.45 m/s^2

the helideck were identified in accordance with professional design standards, such as CAP437 and DNV-OS-E401 (CAA 2013, DNV 2001, Hirdaris, Bai *et al*. 2014). Table 1 shows the load specification during the helicopter landing condition under varying guidance and requirements of Classification Society. As shown, it can be seen that a considerable variation of requirements exists between all the specifications with variations, particularly with regard to (1) the factor on *MTOW* for emergency landing condition; (2) whether a deck response factor is considered; (3) whether the level of superimposed load is considered simultaneously or separately; and (4) whether a lateral load is considered simultaneously with the emergency landing load. In the present study, CAP 437, an up-to-date design guideline, was adopted.

The selection of helicopter must take precedence in order for calculation of landing load subjected to helideck. The Sikorsky S-92 helicopter, which is the most widely adopted model, is selected as the helicopter for this analysis to determine the landing load of the helicopter on a helideck. This helicopter model is a medium-sized transportation helicopter with two pilots and 16 passengers onboard. The length, height, and maximum taking-off mass MTOM are 17 m, 4.7 m, and 12 ton, respectively (Sikorsky 2010). The helideck should be designed to safely resist forces when landing a helicopter. The landing load of the helicopter listed in the design standards is defined as the coefficient *C* multiplied by *MTOM*, as indicated in

$$F_V = 1.3 \times C \times g \times MTOM\ (kN) \tag{1}$$

$$F_L = 0.5 \times MTOM\ (kN) \tag{2}$$

where F_v and F_L are the vertical dynamic and lateral loads of the helicopter, respectively; g is the acceleration due to gravity; and C is the load coefficient. The load coefficient is 1.5 and 2.5 for normal and emergency landing conditions, respectively. The factor of 1.3 is included in the definition of the vertical load to account for the effect of the dynamic impact of the helicopter. The lateral load is distributed across the undercarriage in proportion to the applied vertical load in the direction that produces the most severe loading conditions for each element concerned (CAA 2013).

The distributed load, which includes the self-weight of the helideck, pipe loads, landing safety net, ramp, gutter, and other various pieces of equipment, was determined by referring to actual shipment data and design drawings (deck plate area of 570 m^2). The gravity and inertial forces caused by the motion and acceleration of the ship were considered in accordance with professional design standards for ships (DNV 2011). The specific loads used in the present study are summarized in Table 2. In addition, the design criteria for the helideck structure can be expressed using the allowable stress concept, given by (DNV 2001)

$$\sigma_{allowable} \leq \eta_0 \sigma_{yield} \tag{3}$$

where σ_{yield} is the yield stress of the adopted material, $\sigma_{allowable}$ is the allowable stress for the design criteria, and the parameter η_0 indicates the usage factor. According to DNV-OS-E401, the safety level of the design scheme can be evaluated by conducting a comparative study of the maximum stress (σ_{max}) value, which is obtained by FEA, and the allowable stress ($\sigma_{Allowable}$), which is the maximum unit stress permitted under working loads by codes and specifications. In the analysis process, the usage factor is used to determine the allowable stress of structural members with different values for each landing condition (0.67 and 1.0 for normal and emergency landing conditions, respectively). A relatively low usage factor is applied in the case of the normal landing procedure because a low load is repeatedly applied to the structural member. In the case of the emergency landing procedure, however, a more severe usage factor is applied to assure the safety of the helideck in the actual design.

3. Finite element analysis

3.1 Geometry

In the present study, a preliminary analysis was performed on the helideck structure to investigate the general behavior of the structure under different helicopter landing conditions. Fig. 2 shows a photograph of the steel helideck, which is the target structure of the present study, and how it is mounted on the upper deck of the shuttle tanker. The main structure of the helideck is composed of a deck plate, stiffeners, girders, pillars, and trusses. The deck plate, which is placed on top of the helideck, is designed to be octagonal with a length and width of 26.1 m, in accordance with the offshore helideck design guidelines (HSE). Moreover, the stiffeners are arranged below the deck plate at an interval of 650 mm, whereas the girder is divided into zones such that eight and six zones span the length and width, respectively. Table 3 gives the specific

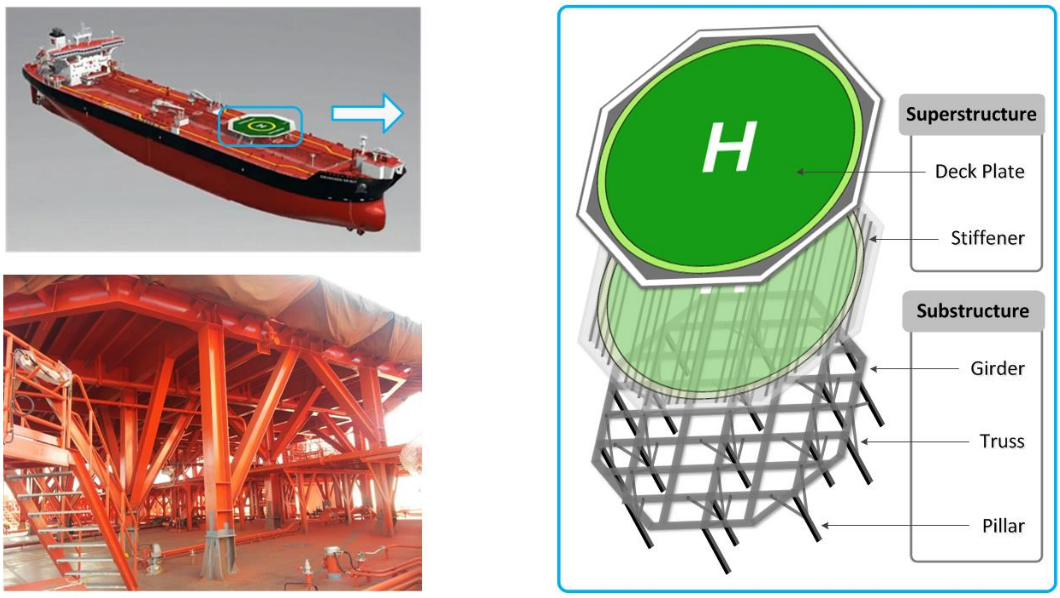


Fig. 2 Installation and assembly of helideck

Table 3 Specific dimensions of the different structural members of the helideck (Park 2014)

Structural member	Dimension (mm)	Mass (ton)
Deck plate	14	62.6
Stiffener	250×90×12/16 I.A	20.6
Transverse web, girder	750×10+250×14(T)	28.1
Pillar	400×16+400×18(H)	30.1
Truss	300×16+300×18(H)	15.6

dimensions of each structural member of the helideck.

3.2 Finite element modeling

Finite element (FE) modeling was performed using the commercial FEA pre- and post-processor MSC Patran 2010, followed by the completion of the design of the offshore helideck geometry. Automatic h-refinement was used to reduce the analytical time and computational costs because it is widely known that the h-refinement method improves meshing precision by increasing the number of elements (Daryl 2008). The elements were 2D surface elements Quad4 and Tri3 that used 107,471 shell and beam elements.

3.3 Loading and boundary conditions

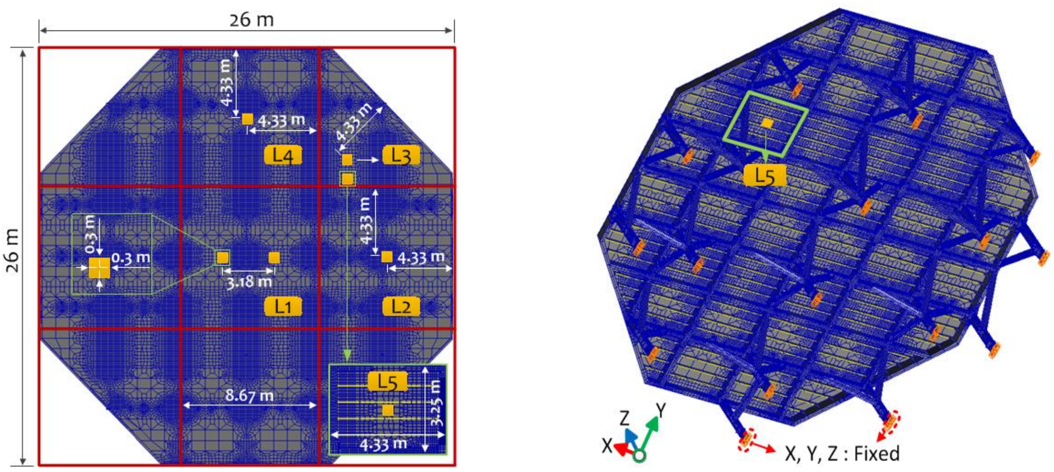
As shown in Fig. 3(a), the helideck is divided into nine sections of equal lengths and widths to apply loads to the helideck. Of the nine sections, only five sections were considered in the analytical scenarios because responses in the remaining sections can be solved by symmetry.

Normal and emergency landing conditions are considered as the two landing load cases. The normal landing conditions are defined as the two rear wheels of the helicopter landing on the top of the helideck and distributing identical loads, whereas the emergency landing conditions are defined as only one wheel of the helicopter landing on the helideck, representing the most severe loading conditions. In the present study, only one case under normal landing conditions is considered, and in this case, the helicopter lands in the center of the helideck (position L1 in Fig. 3(a)). Conversely, four cases under emergency landing conditions are considered, with the helicopter landing in the edge sections of the helideck (positions L2, L3, L4, and L5). The other types of loading, including the self-weight and inertial force, are applied in all conditions. The part of the wheel that comes into contact with the helideck is modeled as a square with sides of 300 mm in accordance with the American Bureau of Shipping (ABS) standards (ABS 2008). Fig. 3(b) shows the boundary conditions of the present preliminary analysis. The helideck is generally installed by fixing the pillars on the upper deck of a vessel. Therefore, the fixed boundary condition is applied to the bottom of the pillars under the deck structure to reflect the actual installation conditions.

3.4 Results of preliminary analysis

The preliminary analysis presented in this study is mainly focused on the emergency landing conditions of the helicopter to perform a structural safety assessment of the helideck, whereas the purpose of the conventional design's consideration of the normal landing conditions is to perform a comparative investigation with the structural response of the emergency landing scenarios. Table 4 gives the preliminary analysis results for each landing position of the helicopter, comparing the maximum stress of each member with the allowable stress under each set of landing conditions. The allowable stresses under the normal and emergency landing conditions are determined to be 211 and 315 MPa, respectively, in accordance with the design criteria of DNV-OS-E401. The stress plot for each landing position on the helideck is provided in Fig. 4.

Under normal landing conditions (L1), which correspond to the as-is design consideration, the landing load of the helicopter is adequately distributed by the substructures of the helideck, including the girder, pillar, and truss. Thus, the maximum stress of the pillar, plate, and stiffener reached 66.8%, 20.8%, and 16.5% of the allowable stress, respectively, showing the elastic behavior of the structure. Under emergency landing conditions at positions L2, L3, and L4, the landing load of the helicopter is adequately distributed throughout the substructure, demonstrating the safety assurance of the helideck, although relatively high stress is concentrated in the transverse web and girder compared with the results under normal landing conditions at position L1. When the helicopter lands at positions L2 and L4, it is mainly supported by the girders and pillars, which is similar to a normal landing at position L1. When the helicopter lands at position L3, the stiffeners experience the highest stress, even though the stiffeners and the substructure receive the bulk of the landing load. The highest maximum stress for landings at position L2 and L4 applied to the truss was 48.57% and 48.88% of the allowable stress, respectively, whereas the highest maximum stress at position L3 was applied to the stiffeners and had a value of 57.4% of the allowable stress. The results indicate that the helideck is sufficiently safe for emergency landings at positions L2, L3, and L4. However, this is because positions L1 to L4 are located on or adjacent to a girder. In order word, in general, the landing load subjected to helideck was distributed by placing the girder at the predictable landing position such as the center of each section.



(a) (b)

Fig. 3 (a) Loading and (b) boundary conditions of the helideck structure

Table 4 Preliminary analysis results for different landing positions (MPa)

Structural member	Normal landing condition		Emergency landing condition				
	L1		L2		L3	L4	L5
	$\sigma_{allowable}$	σ_{max}	$\sigma_{allowable}$	σ_{max}			
Deck plate	211	44	315	56	52	73	103
Stiffener (250 I.A)		35		32	181	80	380
Transverse Web, Girder		65		115	150	127	111
Pillar, Truss		141		153	124	154	134

On the other hand, when the helicopter lands at position L5, which is located in the center of a part that is surrounded by girders as shown in Fig. 3, the magnitude and distribution of the maximum stress were considerably different from the other emergency landing scenarios. At landing location L5, a relatively uneven stress distribution is observed compared to the other emergency landing scenarios. That is, the landing load was not effectively distributed in this landing location along the transverse web and girder, showing approximately 20% excess allowable stress at the stiffeners. As a result, the stiffener may experience plastic deformation caused by emergency landing loads. However, it is difficult to be certain that the helideck is structurally unsafe as a result of this plastic deformation because other supporting structures were designed using elastic theory to ensure no permanent deformations in preparation for emergency landing (HSE 2001).

The results of the preliminary analysis confirm that the maximum stress was highly dependent on the landing location of the helicopter as well as the arrangement of the structural members. However, it is difficult to accurately predict the stress affecting each member of the helideck by performing preliminary analysis alone. In this regard, it is necessary to investigate different methods of determining the distribution of the landing load on each member and selecting parameters that affect the design performance of the helideck. Therefore, a parametric study on each member of the helideck was performed based on the initially obtained results.

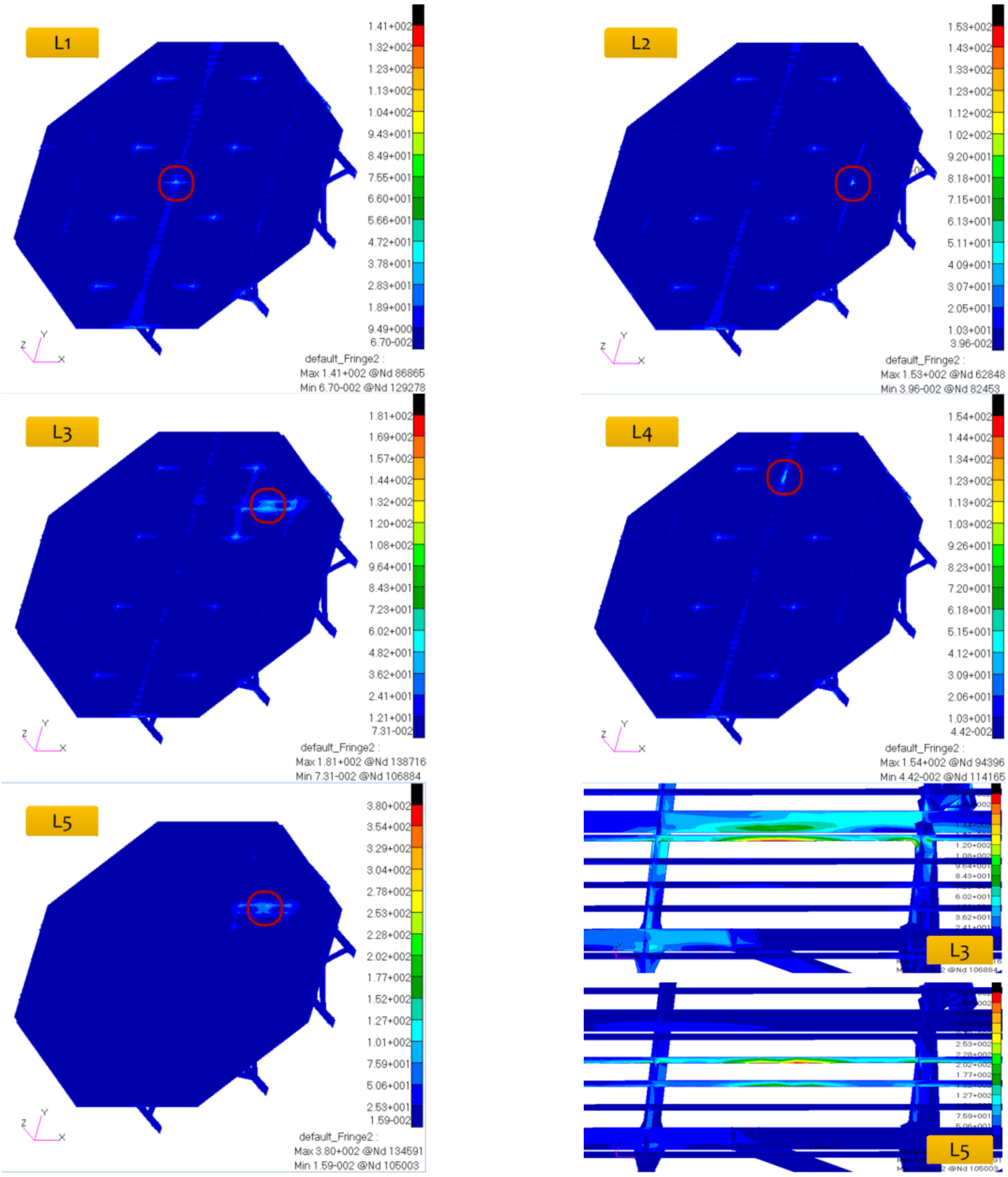
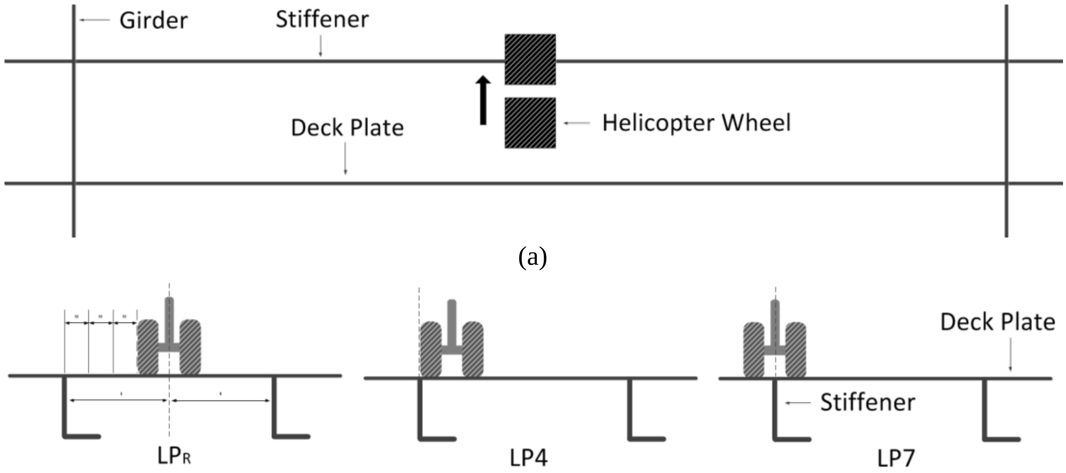


Fig. 4 Stress plot for each landing position

4. Parametric study

4.1 Landing position

In the present study, a parametric study was performed by dividing the helideck into two major structures-the superstructure (plate and stiffeners) and the substructure (girders, pillar, and trusses)-through a linear static analysis using the FEA program. Strictly, a dynamic analysis is required to



(a)

(b)

Fig. 5 Schematic view of the (a) wheel load and (b) landing positions

correctly determine forces within a helideck and its supporting structure. This is because a static approach ignores the energy that is absorbed dynamically and the strain-rate effect of materials. However, the effects of dynamics strain rate enhancement of yield stress have not been quantified for helidecks and similar structures. Thus, until some progress is achieved on either or both of these fronts, the static approach is recommended by Classification Society, CAP 437, and HSE guidance requirement, although this approach provides an additional unknown and, possibly, a differential level of safety (HSE 2001). In previous research, a helideck, which consists of flat plates with primary and secondary beams, is designed using a linear static analysis (Vaghefi, Bagheri *et al*. 2013).

In the general design process, designers should apply loads to the center of the plate, which is expected to increase stress estimations. Then, stiffeners should be installed at positions of weakness to disperse the concentrated stress (HSE 2001). In this manner, a suitable arrangement of plates and stiffeners is determined by calculating the moment of inertia. The helideck of the present target structure is designed by adopting the same procedure. However, it is difficult to determine ideal landing conditions, as described above, because the helicopter does not always land in the center of the helideck. In addition, the stress applied to the plate and stiffeners is very sensitive to the landing position of the wheels. Therefore, the purpose of this section is to confirm the structural response of the helideck to incremental changes in the location of the wheel load from the center of the plate (LP_R), which is the reference point of the general design, to the center of the stiffener (LP7) to consider the actual landing conditions of the helicopter, as shown in Fig. 5. In this process, the emergency landing load of the helicopter was applied to the cross section of the wheel that makes contact with the helideck (300 mm×300 mm). The analytical model used for structural analysis is identical to the preliminary design model. In addition, the maximum stress of each loading position is given in Table 5.

According to the results, the maximum stress variations for the different landing positions showed different trends than those of the general design concept. First, the maximum stress of the helideck did not occur when the loading position was at the center of the deck plate. The maximum stress of the deck plate and stiffener was when the load was applied at the center of the

Table 5 Maximum stress at each loading position

Structural member	Maximum von Mises stress (MPa)						
	LP_R	LP2	LP3	LP4	LP5	LP6	LP7
Deck plate	70	77	83	91	93	96	98
Stiffener (250 I.A)	295	329	353	374	362	344	315

stiffener (LP7) and inside of the wheel aligned with the stiffener (LP4), respectively. Second, the stress of the plate showed little sensitivity to the landing position, whereas that of the stiffener showed high sensitivity. Those differences in the reactions of these two components occur because significant loads applied to the helideck are not supported by the plate but by the stiffener. Third, in all cases except LP_R and LP7, the maximum stress of the stiffener exceeded the yield stress of the material. Therefore, the dimensions of the plate and stiffener such as thickness or depth must be supplemented or controlled to prevent permanent deformation of the helideck caused by helicopter landings at positions LP2 to LP6. In addition, it was confirmed that specific consideration of the landing position should be performed to complement the as-is design considerations that confirm the response at the center of the plate or stiffener only. More details on this subject are introduced in Section 4.3.

4.2 Plate material and thickness

In the helideck design, determination of the plate thickness is one of the most important considerations. The preliminary FEA revealed that the plate thickness can be decreased even when considering emergency landing conditions because the maximum stress subjected to the plate is very low in comparison to the minimum thickness of the plate, which is given in Eq. (7) (DNV 2001).

$$t = \frac{62.4\sqrt{k_w \times b \times s \times p}}{\sqrt{m \times \sigma_f}} \tag{4}$$

$$k_w = 1.3 - \frac{4.2}{\left(\frac{a}{s} + 1.8\right)^2} \tag{5}$$

$$m = \frac{38}{\left(\frac{b}{s}\right)^2 - 4.7\left(\frac{b}{s}\right) + 6.5} \tag{6}$$

where t is plate thickness, s is the stiffener space, p is design pressure, σ_f is the minimum yield strength of the material. In addition, parameters a and b are the extent in meters of the load area parallel and perpendicular to the stiffeners, respectively. Fig. 6 shows the parameters related to the stiffener and wheel area. Symbol l stands for the stiffener length. Eqs. (4) to (6) were applied in the case of s/l=0.4 for the separated platform.

These equations show that the plate thickness should be increased with increasing wheel size, stiffener spacing, and design pressure. However, the thickness of the plate decreases for materials with higher yield stresses. Therefore, the present problem is a function of yield stress and stiffener

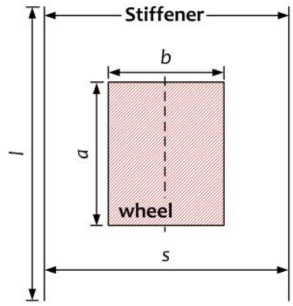
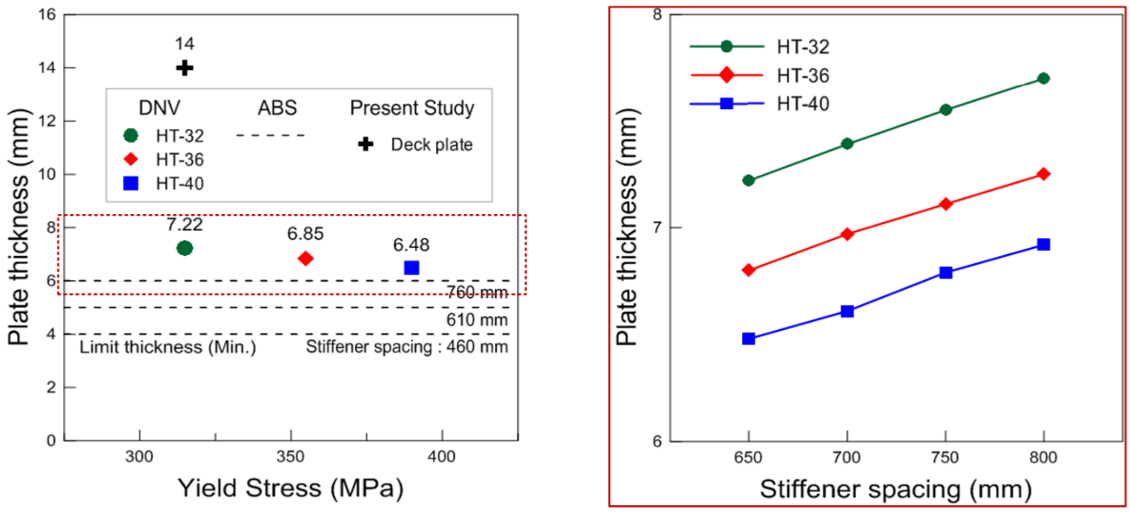


Fig. 6 Parameters related to the stiffener and wheel area

Table 6 Minimum thickness and price of deck plate based on materials

Material	Yield Stress (MPa)	Min. Thickness (mm)	Price (USD/ton)	Total Mass (ton)
HT-32	315	7.22	1072	32.05
HT-36	350	6.85	1100	30.65
HT-40	390	6.48	1160	28.99



(a) (b)

Fig. 7 Minimum thickness of the plate according to stiffener spacing: (a) professional design standards and (b) DNV standards

spacing because wheel size and design pressure are determined by helicopter specifications. Therefore, in this parametric study, in addition to HT-32, HT-36 and HT-40 steels are considered as suitable replacement materials (DNV 2011). In general, using a material with a higher yield stress leads to a thinner plate; however, other factors, such as price and workability, should also be considered. The relationship between the thickness and price of each material can be confirmed from Table 6. When replacing HT-32 with HT-36 for a helideck with an area of 570 m^2, the total weight and price of the steel can be reduced by 1.4 tons and 642.6 USD, respectively.

Fig. 7(a) compares the thickness of the deck plate and the ABS standards. As shown in this figure, the thickness of the deck plate is approximately twice that required by the given standards. The required minimum thickness of the deck plate is 7.72 and 5.26 mm, as specified by the DNV and ABS standards, respectively, when the stiffener spacing is 650 mm and the material is HT-32. Based on these standards, our results indicate that the deck plate of the helideck was designed to be fairly conservative. It can be also said that the present helideck has been safely designed against buckling loads, because the plate thickness of the present helideck was approximately twice as compared to those of the Classification Societies and HES guidance. In addition, the minimum thickness of the plate is investigated for stiffener spacings between 650 and 800 mm. In this case, stiffener spacings of less than 650 mm are not considered, because the maximum stress already exceeds the allowable stress of the material at loading positions LP2-LP6, as indicated in Table 5. As shown in Fig. 7(b), the stiffener spacing was confirmed to have little effect on the minimum thickness of the plate, although the thickness of the plate should be increased with increasing stiffener spacing.

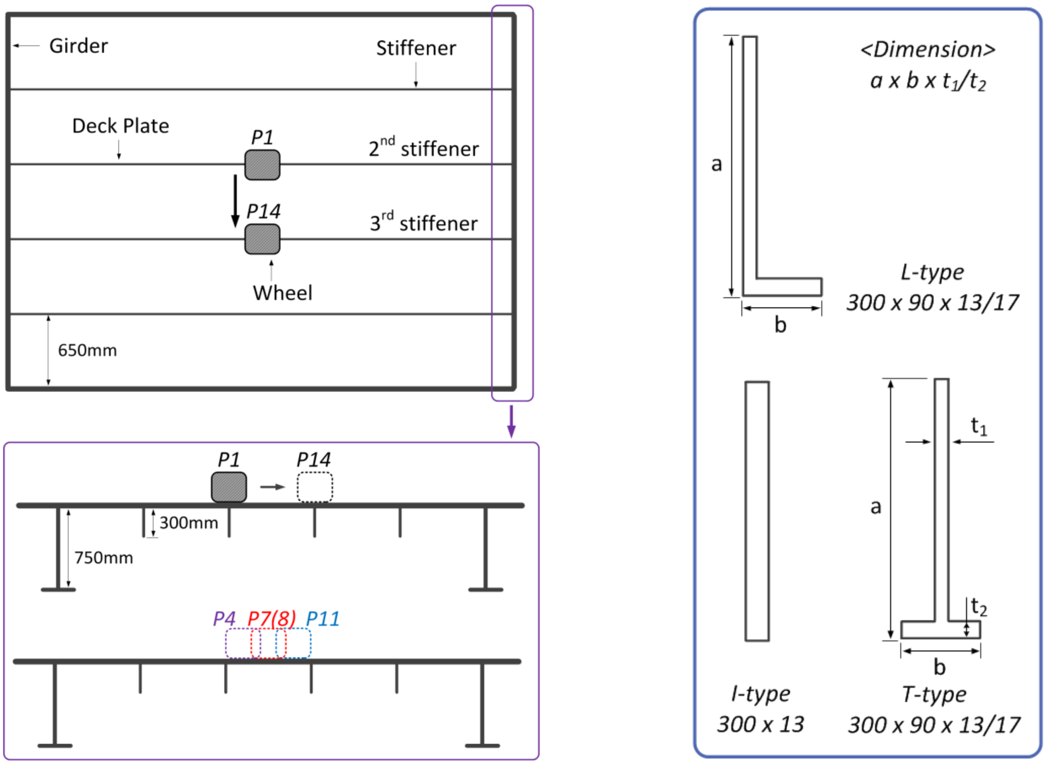
4.3 Stiffener spacing and type

The previous sections, especially Section 4.1, demonstrate that the maximum stress of the helideck is dependent on the landing position, with the maximum stress occurring when the landing position was such that inside of the wheel was aligned with the stiffener. In addition, the designed plate thickness was shown to be conservative compared with professional design standards. However, it is necessary to reconsider the dimensions of the stiffener because the maximum stress of the stiffener exceeded the yield strength of the target material, as shown in Table 5. Thus, in this section, the structural response of the helideck is investigated by changing the stiffener dimensions from 250×90×12/16 (initial design) to 300×90×13/17 (inverted angle).

Table 7 shows the variation in the maximum stress of the deck plate and stiffener depending on the spacing and loading position of the stiffener. In Table 7, the maximum stress of stiffener was approximately 20% lower than that of the maximum stress of the stiffener before changing the dimension of the stiffener. The maximum stress of the plate and stiffener steadily increased with increasing stiffener spacing because each member is able to support additional loading. As previously demonstrated, the maximum stress did not occur for the landing position at the center of the stiffener and plate, but at position LP4.

In Section 4.1, an asymmetric landing position is considered, although the wheel load is translated from the center of the plate to the center of the stiffener. In addition, it is possible that the maximum stress is affected by the landing position because the stiffener is an asymmetric L-type structure and the supporting structures, such as the pillars and trusses, are imbalanced. That is, several previously mentioned asymmetric factors, which apply the maximum stress to the plate and stiffener, are not allowed to be constructed symmetrically.

Therefore, asymmetric results are resolved by making the helideck perfectly symmetric to investigate the effect of the stiffener type (I-, L-, and T-types) and the landing position. To construct a FE model for analysis, nine parts are allocated in a 3×3 matrix. Each part is composed of four stiffeners and four girders, as indicated in Fig. 8(a). In addition, the landing load of the helicopter is applied to points in the central region of the model by moving at intervals of 50 mm from the center of the 2nd stiffener (P1) to the center of the 3rd stiffener (P14). As shown in Fig. 8(a), the supporting structure is not considered, and the points of intersection of the girders, which are the locations where pillars or trusses may be installed, are fixed as boundary conditions. In



(a) (b)

Fig. 8 Schematic view of (a) the locations of the landing load and (b) the stiffener types

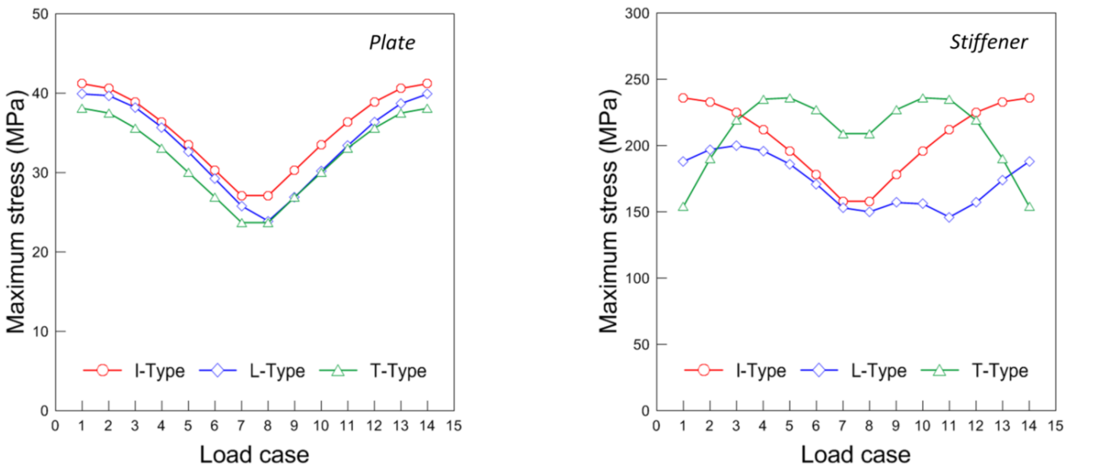


Fig. 9 Maximum stress of the structural members with respect to the landing location and the type of stiffener

addition, three types of stiffeners (I-, L-, and T-type stiffeners) with the same area are considered.

Fig. 9 shows the variation in the maximum stress of the plate and stiffener with respect to the landing load location and the type of stiffener. At first, the maximum stress of I- and T-type

Table 7 Maximum stress of the deck plate and stiffener for different stiffener spacings and loading positions

Structural member	Stiffener spacing (mm)	Maximum von Mises stress (MPa)						
		LP_R	LP2	LP3	LP4	LP5	LP6	LP7
Deck plate	650	58	65	72	77	80	85	90
	700	60	66	76	80	83	88	92
	750	70	74	82	85	87	92	96
	800	70	77	83	91	93	96	98
Stiffener (300 I.A)	650	248	270	290	301	293	275	250
	700	260	292	308	312	300	282	256
	750	285	295	320	341	316	301	265
	800	299	302	324	350	326	313	297

stiffeners showed perfect symmetry around the center of the plate. However, the behavior of the stiffener showed different trends with regard to the landing position, although the plates are similar to each other. For the I-type stiffener, the maximum stress of stiffener showed the lowest and highest maximum stresses for loading positions with the wheel at the midpoint between the stiffeners (P7, P8) and centered above the stiffener (P1, P14), respectively. In contrast, the lowest and highest maximum stresses of the T-type stiffener corresponded to loading positions with the wheel centered above the stiffener (P1, P14) and with inside of the wheel aligned with the stiffener (P4, P11), respectively.

Second, the stiffener generally showed beam-like bending behavior when the load was applied to the center of the stiffener (P1, P14). Therefore, it is expected that the lower stress in the T-type stiffener is caused by a higher moment of inertia. In addition, the lowest stress is observed with the L-type stiffener in almost all landing positions for similar reasons. This means that the L-type stiffener is the most favorable stiffener design when using the same amount of steel because a model equipped with the L-type stiffener can maximize the moment of inertia.

Third, the stiffener is subjected to more stress for the landing positions with inside of the wheel aligned with the stiffener (P4) than for those at the centered above the stiffener (P1) in the case of the T- or L-type stiffeners, as indicated in Fig. 10. The detailed behavior of the T-type stiffener was investigated on the basis of the nearest stiffener at each landing position. The main behavior of the stiffener, which is located below the deck plate, showed downward deflection (z-axis) spreading from side to side (y-axis). The stiffener was deflected in the direction of the load (z-axis), and the maximum stress occurred at the middle part of the flange of the beam when the vertical load was applied to the center of stiffener. The stiffener simultaneously exhibited two main behaviors (deflection in the z-direction and spreading in the y-direction) when a vertical load was applied with inside of the wheel aligned with the stiffener (P4, P11) by moving the location of the vertical load. For this reason, the two deformation behaviors of the stiffener overlapped at the middle part of the flange, and the stress applied to this part is concentrated because the induced stresses caused by each behavior are added. These results confirm that asymmetric stress distribution is more affected by the behavior characteristics of the beam that are dependent on the landing position than the asymmetric structure of the helideck or stiffener.

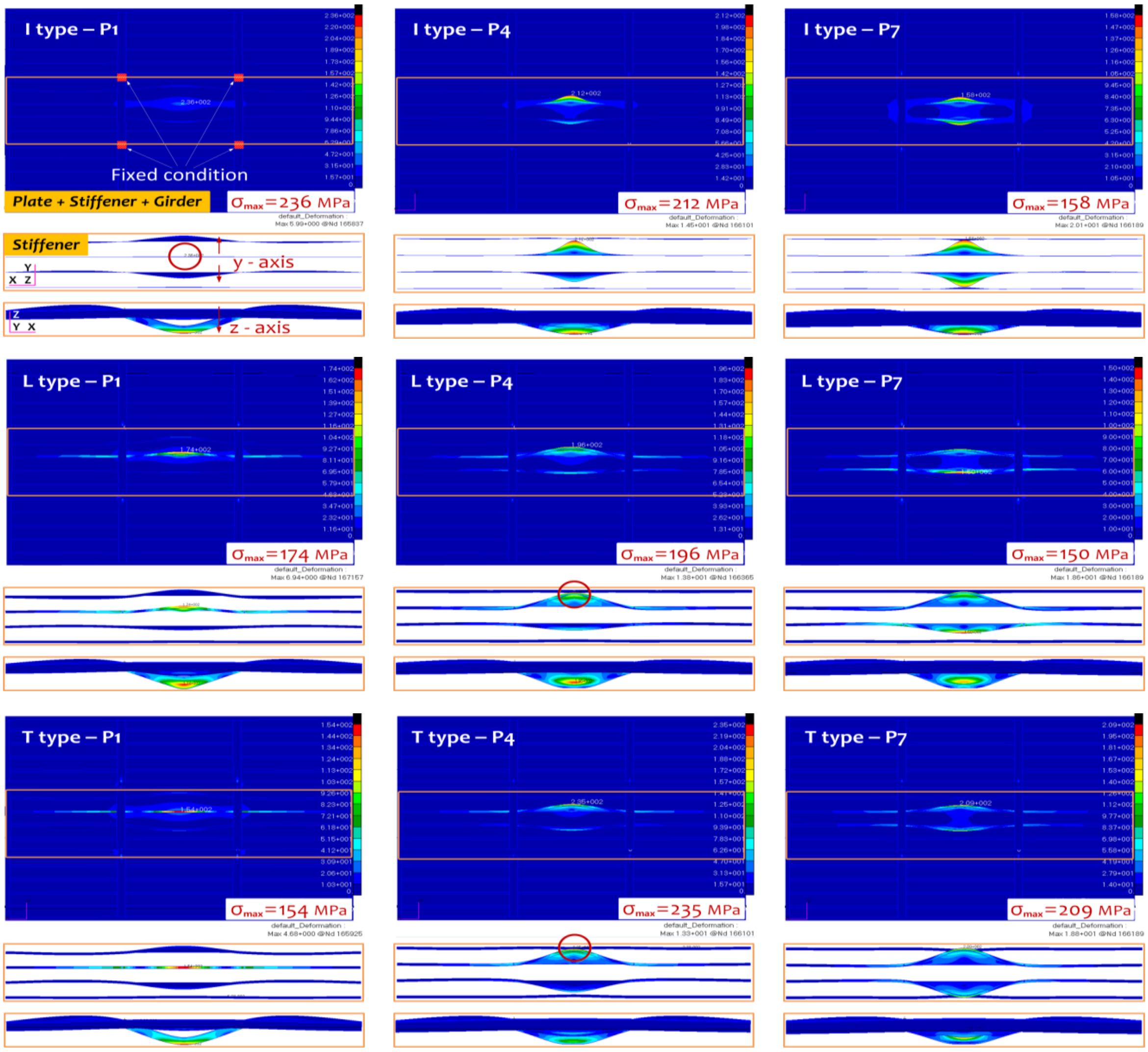
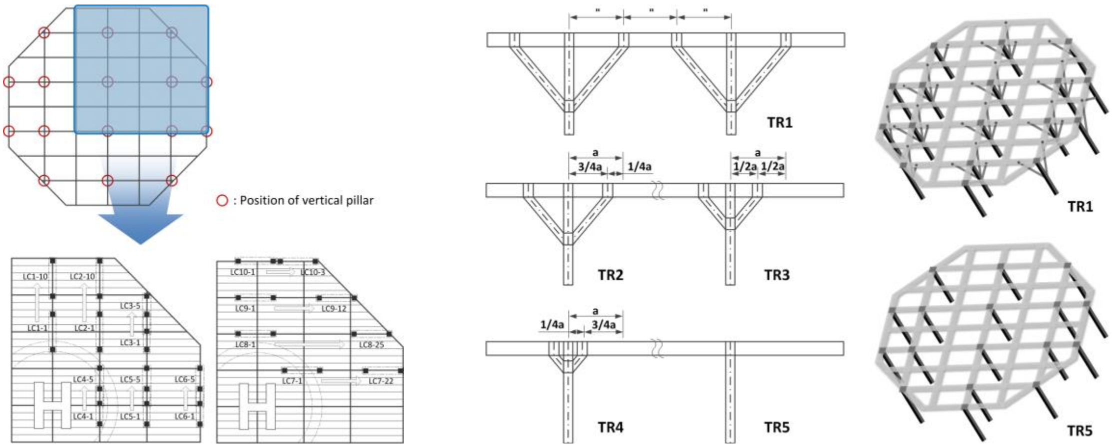


Fig. 10 Maximum stress of the 3×3 model for different types of stiffeners under loading positions

4.4 Supporting structure: girder depth, truss shape, and pillar position

A parametric study on the substructure excluding the deck and stiffeners was conducted for the case in which the helicopter lands directly on the girder of the helideck. In addition, the helicopter lands on the helideck with the wheels of the two landing gears, and the landing load of the helicopter is distributed between two main undercarriages (CAA 2013). The arrangement of the longitudinal girder and the spacing of the transverse web were maintained as those of the mother ship in the initial design. The analysis was performed on the girder by reducing its depth from 750 to 500 mm at intervals of 50 mm because the depth of the girder is typically designed to be more than twice the depth of the stiffener (HSE 2001). In addition, in this study, to investigate the overall response of the girder and transverse web, a parametric study on various load cases was



(a) (b)

Fig. 11 (a) Transverse load cases (LC1 to LC6) and longitudinal load cases (LC7 to LC10) and (b) schematic plan of trusses

conducted by classifying the expected load cases from LC1 to LC10, as shown in Fig. 11(a). Through this process, the response of almost every point for each considered landing load was confirmed.

In addition, to verify the effectiveness of the truss, the response of the girder was confirmed by reducing the truss size, as shown in Fig. 11(b). The initial arrangement of the truss was such that the truss was divided into three equal parts. Furthermore, four cases were considered from the initial truss condition (TR1) to the removed truss condition (TR5), and the conditions were defined as TR1 to TR5.

To perform structural analysis combining the variations in the girder depth, load cases (LC1-LC10), and truss arrangements (T1-T5) described above, the dedicated analysis tool for beams, the Nauticus Hull 3D Beam software by DNV, was used before structural analysis was performed using Patran and Nastran (DNV Software 2006). This program is suitable for minimizing the modeling time and evaluating the basic structural design through simple modeling with beam members. Thus, in this study, the response of the members to the landing load of helicopter using this program was first confirmed, and then, based on the results, verification was conducted using an FEA program. As a result, the maximum stress was derived by FEA using Nauticus Hull 3D Beam software for each condition, as described below.

Fig. 12 shows the maximum stress with respect to the girder depth. In general, the maximum stress of the structures increases when truss size or girder depth is decreased. Similarly, it is confirmed that the maximum stress of the substructure showed an increasing trend as the girder depth decreased. In addition, lower stress was observed for the structures with trusses compared with that without trusses. In particular, the case of LC10 showed the highest stress compared with the other loading cases because the substructure acts as a cantilever. In addition, the depth of the girder could be decreased to 550 mm in the case of TR1 when HT-32 is used, whereas the girder depth should be maintained above 650 mm in the case of TR5 to withstand the landing load of the helicopter. However, this limitation can be improved by using a material with a higher yield strength. The maximum stress of the substructure did not exceed the allowable stress of the material except in case LC10. Load case LC10 corresponds to loading at the outermost region of

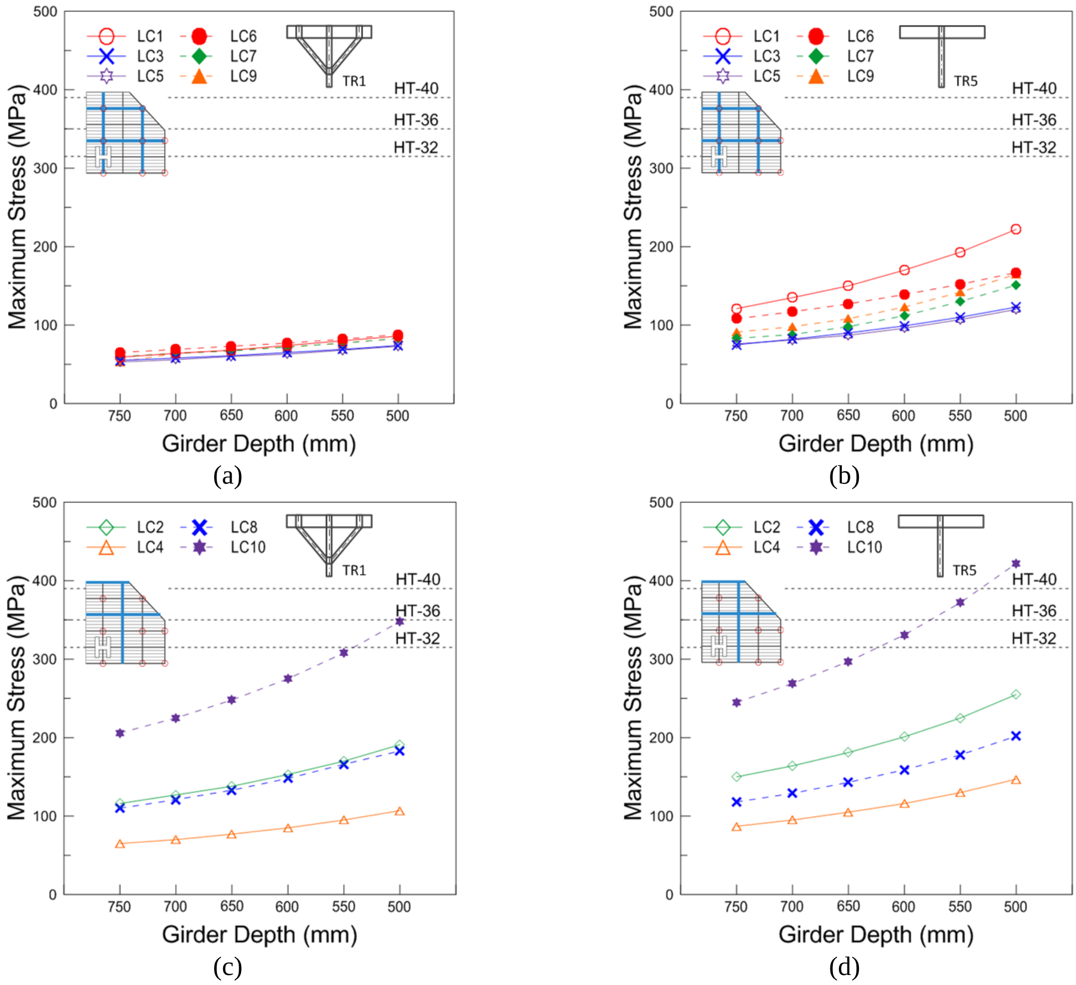


Fig. 12 Maximum stress under load cases (a) with pillar and truss, (b) with pillar and without truss, (c) without pillar and with truss, and without pillar and truss

the helideck. Thus, designers must decide whether to design the helideck to be very safe by considering such extreme landing conditions or to design it economically by excluding such particular cases to decrease the cost of the raw materials.

Fig. 13 shows the ratio of the maximum stresses with respect to the girder depth and truss shape for each load case to investigate the dependency on these variables. Figs. 14(a) and (b) show the ratio of the maximum stress of the substructure with trusses to that without trusses with respect to the girder depth for different load cases. Fig. 13(c) and (d) shows the ratio of the maximum stress with the minimum girder depth to that with the initial girder depth with respect to the truss shape for different load cases.

First, Fig. 13 demonstrates that the ratio of the maximum stresses is dependent on the load case through the differences between the trends in Figs. 14(a) and (c) and those in Figs. 14(b) and (d). In other words, the ratio of the maximum stresses increased with decreasing truss size or girder depth in cases LC1, LC3, LC5, LC6, LC7, and LC9, whereas it remained almost constant in cases

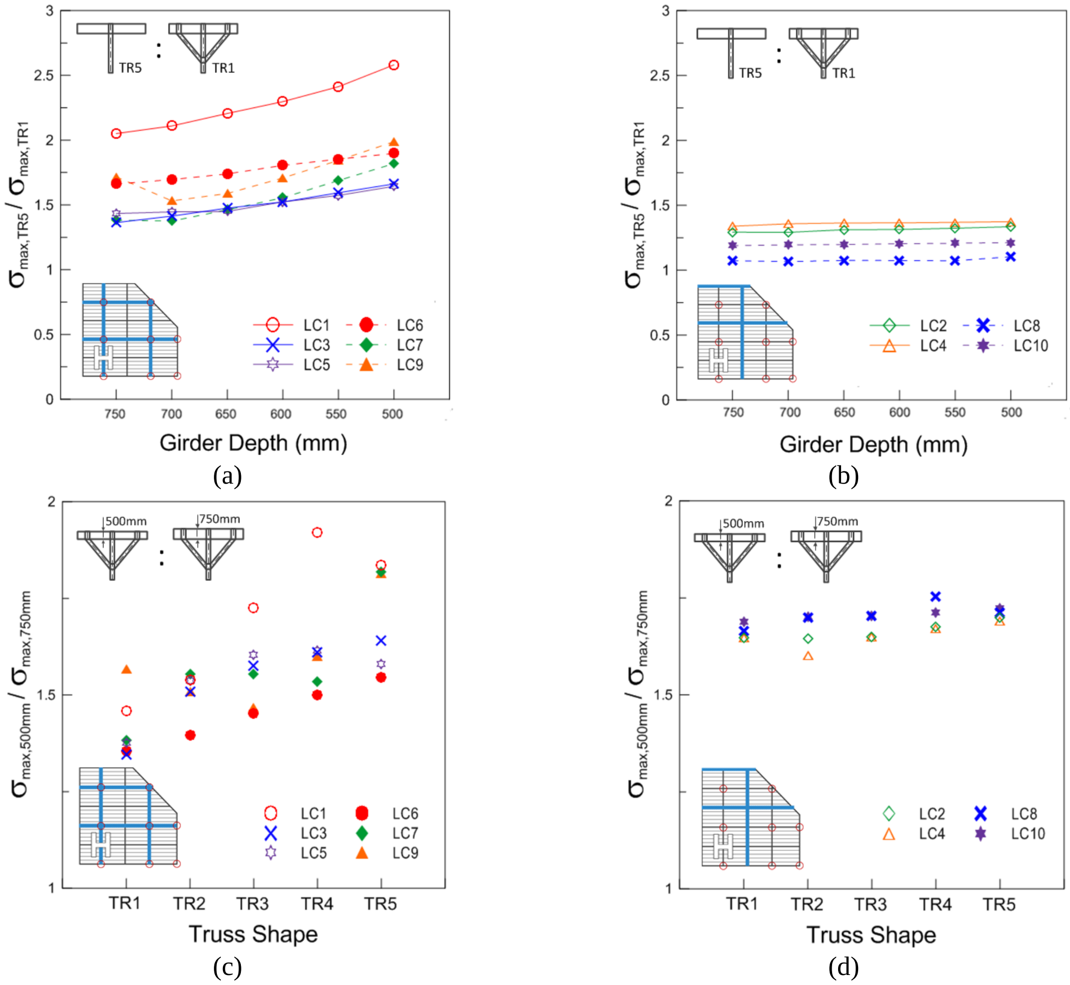


Fig. 13 Ratio of maximum stresses with respect to the girder depth and the truss shape for different loading cases: load cases (a) with pillar, (b) without pillar, (c) with pillar, and (d) without pillar

LC2, LC5, LC8, and LC10. This is the result of whether or not there is a vertical pillar below each landing position; all of the load cases except for LC2, LC4, LC8, and LC10 have vertical pillars below the landing position, and the existence of a vertical pillar makes the substructure sensitive to certain variables.

Second, for landing positions without a vertical pillar, the maximum stress ratio is highly dependent on the girder depth. As shown in Fig. 13(d), the ratio of the maximum stress with the minimum girder depth to that with the initial girder depth is above 1.65, although this ratio is roughly constant with respect to the truss shape. In addition, Figs. 13(c) and (d) confirm that decreasing the girder depth leads to a rapid increase in the maximum stress of the substructure in all load cases. In such cases, the landing load of the helicopter is mainly supported by the girder because the pillar and truss are not installed immediately below the landing position. Therefore, the stress for landing positions without a vertical pillar is more dependent on the girder depth than for landing positions with vertical pillars.

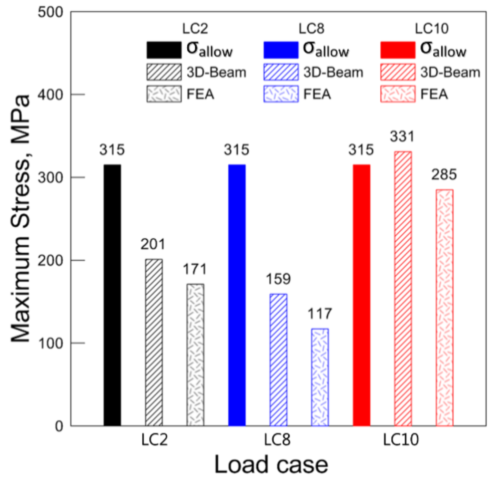


Fig. 14 Comparison of results of Nauticus Hull 3D Beam analysis and FEA

Third, in comparison with the girder depth, the truss shape has relatively little effect on the substructure in all load cases. In the case of the substructure without a truss (TR5), the maximum stress of the substructure increased by 10% to 158% compared with the initial truss shape, as shown in Figs. 14(c) and (d). However, the difference in the maximum stress is not significant, although the existence of the truss is magnified by decreasing girder depth. The highest increase in the maximum stress above 130 MPa is observed for a girder depth of 500 mm at LC1. However, its maximum stress is not seriously considered when designing the substructure, because the overall maximum stress at LC1 is remarkably low compared with the yield strength of material. Therefore, the installation of the truss is very meaningful because it disperses the landing load of the helicopter to other areas, preventing the deformation of the helideck by supporting the lateral load applied to the substructure.

This study on the variables affecting the design of the substructure confirmed that the landing load of the helicopter is mainly supported by the vertical pillars for landing positions above vertical pillars, whereas the stress for landing positions that are not above a vertical pillar is significantly affected by the girder depth. In addition, the truss shape showed relatively little influence on the stress compared with other variables in light of the supported vertical load. Therefore, the adoption of relatively thin girders in the locations with pillars and relatively thick girders in the locations without pillars is recommended.

4.5 Verification of finite element analysis

The main loading condition that affects the behavior of the helideck substructure is bending under the landing conditions of a helicopter, although various loads are applied to the substructure. To understand this loading condition, it is necessary to determine proper element types prior to conducting FEA. In the present study, the analysis program Nauticus Hull 3D Beam is used for the substructure analysis to reduce modeling time and difficulties. The obtained results were compared with FEA results using Patran and Nastran software to overcome the limitations of the analysis using beam elements, such as local stress concentration and non-deformation of the cross section. In addition, the reliability of the analysis results was ensured through verification.

For this reason, structural analysis was performed for loading cases LC2, LC8, and LC10, which showed high stress values for a girder depth of 600 mm and with no trusses (TR5). The structural analysis results of the three load cases are as follows (Fig. 14). In order to assume the severe condition, the girder depth is determined to be 600 mm, which is twice the revised stiffener depth because the girder depth is typically designed in this manner. In addition, the truss was removed. As a result, there is a slight difference between the results of the beam and the FEM structural analysis. In addition, the maximum stresses of the FEM analysis have low values of approximately 16-35% compared with those of the Nauticus Hull 3D Beam analysis. Using these results, it can be predicted that the maximum stress exists within the range of the allowable stress and the helideck is structurally safe for all load cases except LC10. Furthermore, this is a proper assumption because the substructure is composed of simple beams that are long and slender or truss-type structures. Therefore, the design of the helideck determined using Nauticus Hull 3D Beam analysis is generally suitable for investigations of the response of the substructure, although its results are more conservative than those of the FEM program.

5. Conclusions

In the present study, a new design procedure for an offshore helideck was proposed to overcome the limitations of previous studies. A brief summary of the results of this study is given below.

- FEA focusing on emergency landing conditions was performed targeting a steel helideck. The preliminary analytical results revealed significant dependency on the landing location and an inability to effectively distribute stress to each member, such as the deck plate, stiffeners, and substructure.
- A parametric study was conducted to predict the specific stress concentration of each member, distribute the landing load to each member, and select parameters that affect the design performance of the helideck based on the obtained preliminary analytical results.
- The effects of the detailed landing position, material, thickness, stiffener type, and stiffener intervals were specifically investigated. In addition, from comparative investigations, it was found that the L-type stiffener is preferred in almost all landing positions.
- The results for the substructure of the helideck confirmed that the landing load of the helicopter is mainly supported by the vertical pillars, whereas the girder depth significantly affects the structural response of the substructure when the helicopter lands in locations where no vertical pillar is present. In addition, the effect of the truss shape on the substructure was low in comparison with the effects of other variables.
- The FEA results of the helideck were verified by performing a comparative study between FEM (2D) and beam analysis. As a result, it was confirmed that the design using beam elements is suitable to investigate the substructure, although the results are somewhat conservative.

The present study focused on the design contents of the helideck from selecting the helideck (and helicopter) to performing parametric studies on each member. In addition, the existing design standards and precautions that are related to the helideck design were introduced. The results obtained in the present study can provide useful references in the design of similar offshore structures.

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