Sensitivity analysis of the influence of damaged location on mid-ship section of an Aluminum super slender catamaran(HARTH vessel)

Ebrahim Soleimani[1], Mohammad Saeed Seif[*2]

[1*]PHD Student, Mechanical Engineering Department, Sharif University of Technology , Soleimani_e@kish.sharif.edu

[2]Mechanical Engineering Department, Sharif University of Technology, Seif@sharif.edu

Abstract:

The ship structures are at risk of taking damages in many ways. The damage area can be of different locations and shapes. In the current study strength of aluminum damaged sheets has been studied using finite element analysis software. It was found that the closer the damage location to the edges of aluminum plates, the lower strength of plate under buckling due to decrease in effective width. Also it was found that as long as the width of damages are constant, the shape of damages have minor effect on strength of plates. In order to study the buckling behavior of a combination of plates and stiffeners in intacted and damaged conditions, a mid-ship section of a novel aluminum super slender catamaran(HARTH vessel) is modeled under bending moment. It was observed that, if damages are located on deck and bottom area, the total strength is decreased significantly.

Keywords:

Super slender catamaran, Buckling, Finite Element Approach (FEA), Post Buckling Behavior, Aluminum Hull Structure, Compressive Axial Force, Ship damage

تجزیه‌وتحلیل حساسیت تأثیر مکان آسیب‌دیده در بخش میانی کشتی یک کاتاماران فوق‌العاده باریک آلومینیوم (کشتی HARTH)

ابراهیم سلیمانی[۱]، محمدسعید سیف[۲]

۱- دانشجوی دکتری، دانشکده مهندسی مکانیک، دانشگاه صنعتی شریف، تهران، ایران

۲- استاد، دانشکده مهندسی مکانیک، دانشگاه صنعتی شریف، تهران، ایران

چکیده

سازه شناورها به روش‌های مختلفی ممکن است در معرض آسیب قرار گیرد. آسیب ممکن است در قسمت‌های مختلف شناور و به شکل‌های متفاوتی مشاهده گردد. در این تحقیق، ورق‌های آلومینیومی آسیب‌دیده به‌صورت عددی موردمطالعه قرار گرفته است. در این تحقیق مشاهده گردید که هرچه محل آسیب به لبه‌های ورق‌های آلومینیومی نزدیک‌تر باشد، استحکام خمشی ورق‌ها کاهش خواهد یافت و همچنین مشاهده گردید که شکل آسیب، تأثیر کمی در استحکام ورق دارد. در این تحقیق، برای بررسی تأثیر آسیب بر مجموعه‌ای از ورق‌ها و استحکام‌دهنده‌ها در دو حالت سالم و آسیب‌دیده، مقطع میانی یک فروند شناور هارث تحت گشتاور خمشی موردبررسی قرار گرفت. مشاهده گردید که درصورتی‌که آسیب ایجادشده در ناحیه کف و دک شناور اتفاق افتد، کاهش استحکام در کل شناور به‌طور قابل‌توجهی افزایش خواهد یافت.

1. INTRODUCTION

Metal sheets are widely used in buildings, bridges, aviation and marine structures and etc. Aluminum is gaining acceptance in load carrying structures, where a high strength/weight ratio and durability is an advantage. Stiffened plates in aluminum are extensively used in a variety of civil engineering and marine structures as basic elements. These stiffened plates are required to resist extreme loading conditions, e.g. in term of axial compressive loads or lateral pressures. Analyzing these sheets are necessary for every structure in which are used. In the last decade, the analytical, experimental and numerical methods are employed for this purpose. Analytical methods can be rather complex, especially in presence of damage. Since experimental methods are costly and they are usually employed in final stages of numerical analysis. The numerical method is expected to be useful in an efficient and safe design process [1]. There are a few researches, regarding such constructions in aluminum [2, 3]. Spencer (1975) and Henrickson (1982) [4, 5] presented a new structural arrangement for building of aluminum-stiffened plates. Latorre et al. (1997&1999) [6–7], based on some numerical and experimental investigations, applied such a structural configuration in the hull of a catamaran and reached at the conclusion that this configuration is an effective alternative for the regular orthogonal configuration of stiffened plates with fixed longitudinal stiffeners and fixed transverse frames. The ultimate strength of aluminum (AA5083-O and AA6082-T6) plates under the biaxial loading was investigated by Kristensen and Moan(1999), who demonstrated numerically the effect of heat-affected zone (HAZ) and residual stresses on the ultimate strength of rectangular plates on the subject of ultimate limit state design of multi-hull ships made in aluminum[8]. G. Wang et al.(2000) presented the residual strength of damaged ship hull [9]. El-Sawy et al.(2001) carried out the Effect of aspect ratio on the elastic buckling of uniaxially loaded plates with eccentric holes[10].The impact of initial imperfections due to the fusion welding on the ultimate strength of stiffened aluminum plates was studied by Paik et al.(2006) [11] and Collette(2007) [12]. Paik et al. [11] defined the fabrication-related initial imperfections of fusion-welded stiffened aluminum plate structures at the three levels. Also Paik et al. (2007), Derived empirical formulations for predicting ultimate strength of stiffened aluminum plates under axial compression [13]. Mohammad Reza Khedmati et al. (2010) studied on the post-buckling behavior and strength characteristics of the aluminum multi-stiffened panels under combined axial compression and lateral pressure [14]. J. M. Underwood et al.(2012), presented a research, based on ultimate collapse strength assessment of damaged steel-plated structures [15]. S. Gui-Jie and W. De-Yu (2012) presented an experimental research to evaluating the ultimate strength of a steel container ship's structure and reported the same results about stress contributions [16]. Saydam et al. (2013) studied on Performance assessment of damaged ship hulls [17]. N.E. Shanmugam et al. (2014) had some experimental researches on stiffened plates subjected to combined action of in-plane load and lateral pressure [18]. M. Tekgoz et al. (2015) worked on the effect of residual stress on the ultimate strength of a thin rectangular stiffened and single plate [19]. Yan Zhang et al. (2017) had some researches, to define ultimate strength of hull structural stiffened plate considering to corrosion damage, under uniaxial compression [20]. Ming Cai Xu and C. Guedes Soares(2013) presented a research to study the influence of local dent on the collapse behavior of stiffened panels[21].Irene C. Scheperboer et al.(2016) considers local buckling of perforated square aluminum plates.in their research, Plates of various slenderness with simply supported edges and subjected to uniaxial compression are studied, using the finite element method[22].S. Saad-Eldeen et al.(2016) worked on ultimate compressive strength of highly damaged plating resulting from dropping objects, grounding or collision[23].Malgorzata Witkowska and C. Guedes Soares (2015), studied the behavior and ultimate strength of locally damaged plate panels [24].Burak Can Cerik(2015), focused on the load-carrying behavior of large diameter thin-walled stiffened cylinders with local damage when subjected to axial compressive loading[25].Zhigang Li et al.(2015) had an experimental test to investigate the effect of local dents on the residual ultimate strength of 2024-T3 aluminum alloy plate, used in aircraft under axial tension tests[26].S. Saad-Eldeen et al.(2015) analyzed the local and the global structural behavior of rectangular steel plates with a local dent[27].M.Mohammadi et al.(2015) presented a research based on calculating of global loads on a trimaran in intacted and damaged conditions[28].Anuar AbuBakar and R.S. Dow(2013) had some researches to compare the numerical simulations and experiments investigating the grounding of ships[29].Bin Liu, C. and Guedes Soares(2015) presented a simplified analytical method to examine the crushing resistance of web girders subjected to local static or dynamic in-plane loads[30].Bin Sun et al.(2015) proposed an analytical method based on plastic mechanism equations for the rapid prediction of the response of a ship's side structure subjected to raked bow collisions[31].J.N. Marinatos and M.S. Samuelides(2015) presented the definition of a procedure for the numerical simulation of the response of ship structures under accidental loading conditions[32]. soleimani et al. (2019) presented the parametric study of buckling and post- buckling behavior for an aluminum hull structure of a high-aspect-ratio twin hull vessel[33].

1.1. Effect of damage on sheet strength

There are lots of studies on strength of marine structures in the presence of damage which can be the result of collision or explosion. In many of these studies damaged is modeled as a hole with ordered shape. Kumar et al.(2007), studied the strength of steel plates having holes with different shapes and sizes in the center under axial pressing force. They detected three essential factors for determining the strength of plate: Aspect ratio of plate, aspect ratio of hole and plate slenderness ratio, which is expressed by the following equation [34]:

$$\beta = \frac{B}{t}\sqrt{\frac{\sigma_y}{E}}$$

In which B is the width of the sheet, t is its thickness, σ_y, yield strength and E elastic modulus of material respectively.

Yu et al. (2012) performed similar studies on the effect of plate’s thickness and aspect ratio and area of damage on buckling strength of steel plates. They found out that in case the larger edge of damage is perpendicular to axis of loading, plate’s strength is highly dependent on thickness and damage’s aspect ratio and location of damage has no effect on strength. But in case the larger edge of damage parallel to loading axis the effect of damage location will be dependent on thickness. They also proposed relations for strength as function of this variables [35].

Underwood et al. (2012) studied the strength of steel plates under buckling condition after damage. It was tried to study the effect of thickness and aspect ratio and area of damage. The shapes of damage were triangular, rectangular and oval. They found out that, the shape of damage is of minor effect and area and location of damage have significant effect on strength [36].figure 1 shows a kinds of damage that is occurred in a ship structure [37].

Figure 1: Damage in a ship structure[37].

In current research, it is tried to study the buckling behavior of aluminum plate under uniaxial compressing force using finite element method. Especially the effect of damage location, size and geometric shape are the other objects of this paper. First the method employed is described and then number of analysis are performed with variation of described variables. For analyzing a combination of plates and stiffeners, a mid-ship section of a novel super slender twin hull is modeled and exposed to bending moment with different damaged conditions. The effect of damage location on strength of this aluminum novel structure is studied by defining damage in number of locations. Because of high aspect ratio (length to width ratio) of this novel vessel, the mid-ship section, is the most probable section that imposed to buckling, and up to now, few researches have been carried out on this kinds of vessels and studying of buckling strength, with presence of damage, on mid-ship section of this aluminum vessel is very important for designers.

2. Results and analysis

2.1. Effect of damaged location on strength of plates

First, the linear buckling analysis of plate was performed. Buckling modes and eigenvalues were extracted. Plate was considered simply supported and under uniaxial compressing force. Two first buckling modes are displayed in figure 2. Plate's dimensions were 500 × 500 mm [33].

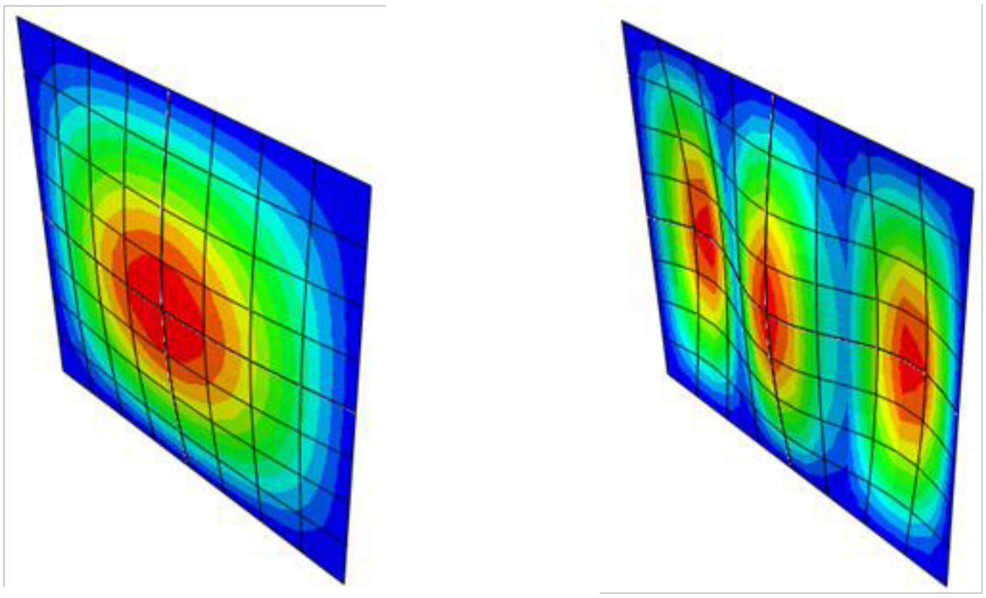


Figure 2: Plate's buckling modes[33].

In order to evaluate the impact of damage location on the strength of sheet, 250 different location for damage, was introduced and linear analysis was performed for each cases. The area of damage was constant and relatively large, so reduction in strength was obvious (Figure 3). Results are shown as a three dimensional map in figure 4. Blue dots demonstrate the position of center of damage and x and y are longitudinal and transverse dimensions respectively; while z demonstrates strength of plate for each case. Due to symmetry, only half of plate was analyzed. It is obvious that plate has higher strength when damage is close to its center and as it moves toward the edge of plate, its strength is notably decreased. This is more noticeable when damage is close to longitudinal edges.

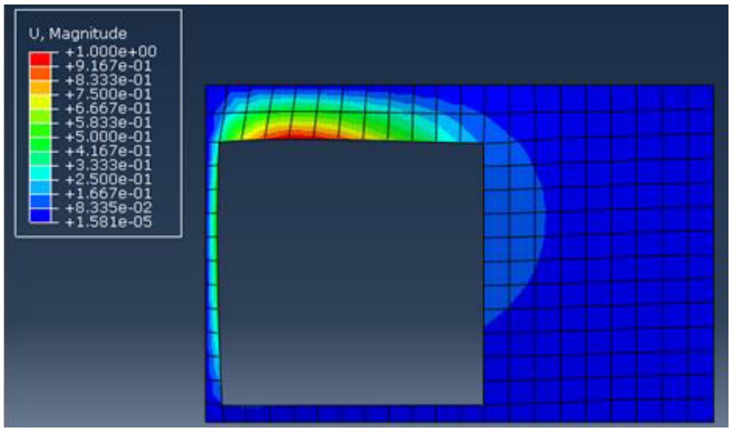


Figure 3: typical dagamed plate.

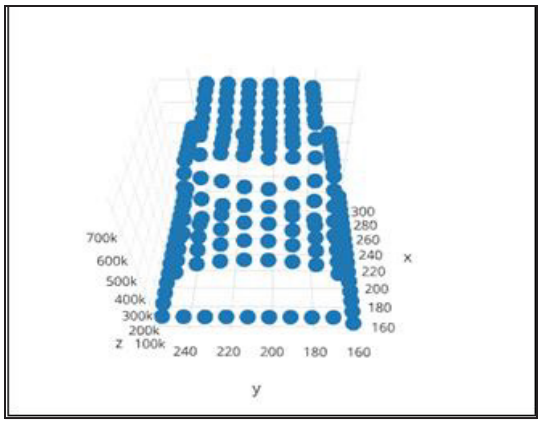


Figure 4: Strength of plate with different locations of damage.

2.2. Effect of damage’s shape and size

2.2.1. Linear analysis

Figure 5 shows the effect of area of damage to the area of the sheet on its strength in linear analysis. According to this curves, strength of sheet is highly dependent on the area of damage to the area of the sheet and its increasing, will cause to reduce the strength significantly. It is also noticed that shape of damage has a minor effect on sheet’s strength. So it seems that, in case that the damage area is constant, strength of sheet is independent of the geometry of the damage.

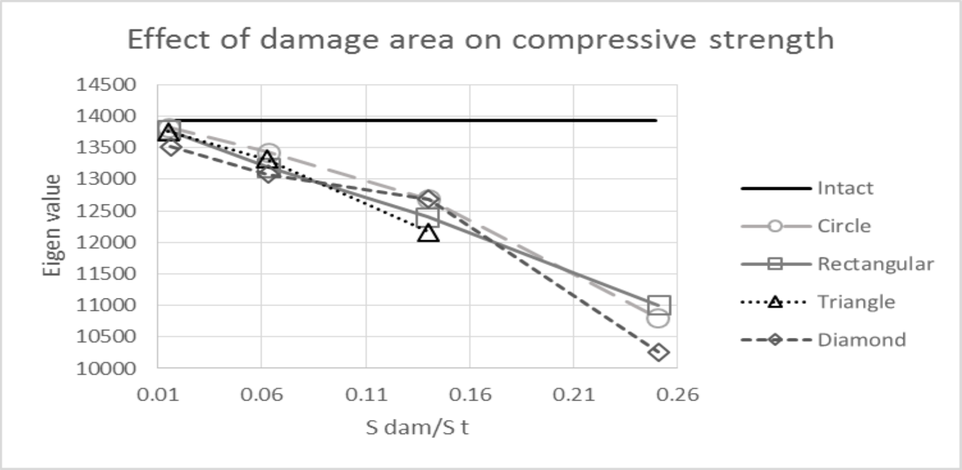


Figure 5: Effect of damage area on plates strength-Linear FEA.

2.2.2. Non Linear analysis

Figure 6 shows the effect of damage’s area with different shapes on the strength of sheet. According to this curves, the area of damage has a high impact on strength of sheet. On the other hand, it seems that strength of sheet is also depends on the shape of damage, especially for larger damages. For smaller damages, the strength of sheet is almost the same for all shapes of damage. The reason of this, is related to the damage’s location.

In current analysis, the damage is located in the center of the sheet. Since sheet is more rigid along the edges, it bears more loads in these regions. As for center of the sheet with higher degrees of freedom for nodes, the stress levels are lower (Figure 7). So a damage in these region, has lower impact on strength. For a detailed analyze curves of damage's width, effect on sheet's strength were extracted. As can be seen in figure 8, strength of sheet has lower dependence on damage's shape according to this criterion and the strength of sheet is related to the damage's width.

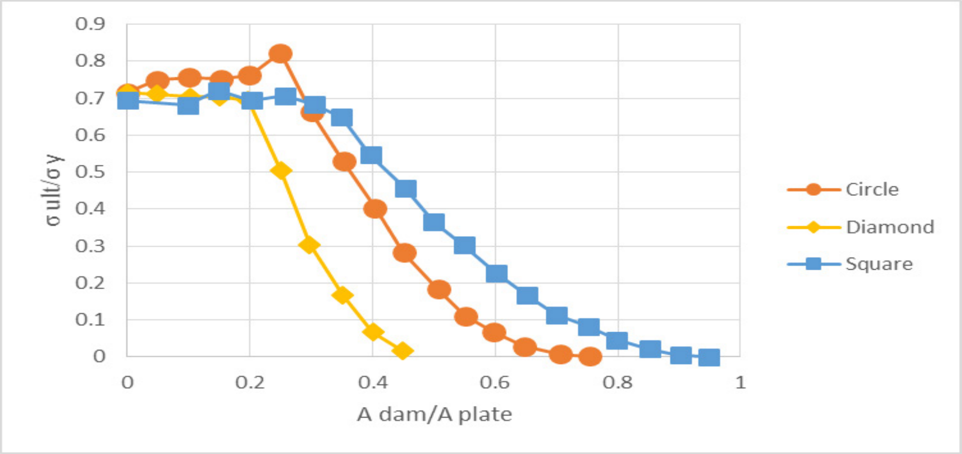


Figure 6: Effect of damage area on plates strength-NonLinear FEA.

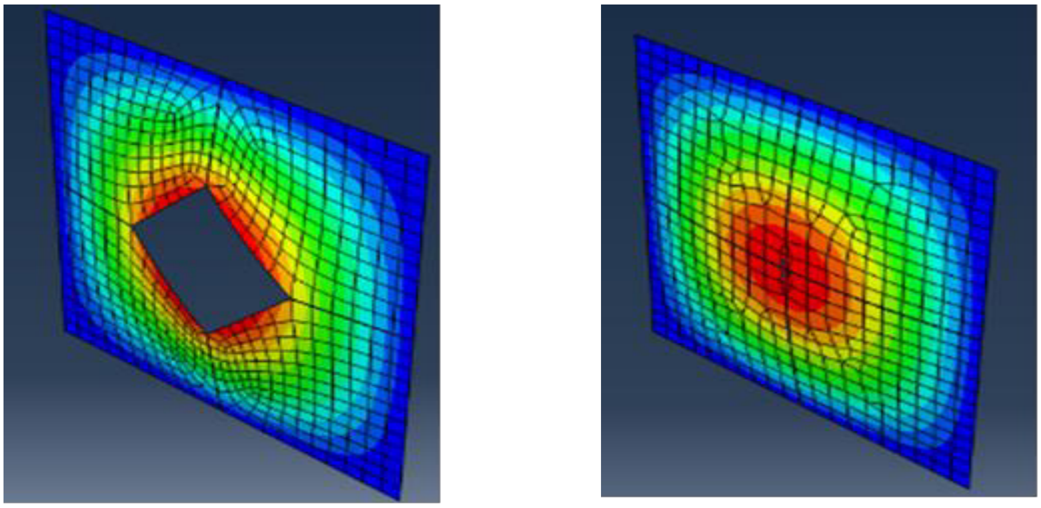


Figure 7: Elements displacement in plate.

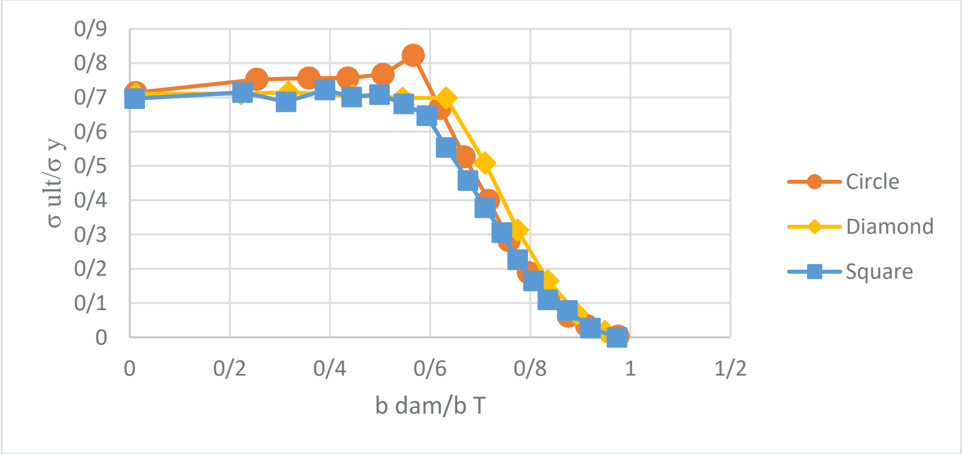


Figure 8: Effect of damage width on plates strength-NonLinear FEA.

2.3. HARTH Vessel

In recent years, research on High Speed Craft (HSC) has attracted many researchers. Throughout the history, human beings have always sought to accelerate the evolution of boats for military, commercial or recreational purposes. Naval architects have developed several methods for measuring and evaluating the dynamic behavior of HSCs. Among the hull forms presented in recent years, is HARTH (high aspect ratio twin hull) concept that has some interesting features from the designer's point of view [38]. This vessel is same as Catamarans from the geometrical viewpoints. The differences of this vessel with the conventional catamarans include the length of pontoons (high aspect ratio) and the height of the cross deck. These two subjects, on one hand, increase the aspect ratio (length to width ratio) on these vessels and, on the other hand, prevent the deck slamming and reduce the magnitude of applied loads on the hull. This makes the vessel able to maneuver easily in harsh seas and significantly improve its ability to move in waves. Figure 9 shows the section of these bodies that changed from conventional monohull to navel catamaran with high aspect ratio twin hull (HARTH) [33].

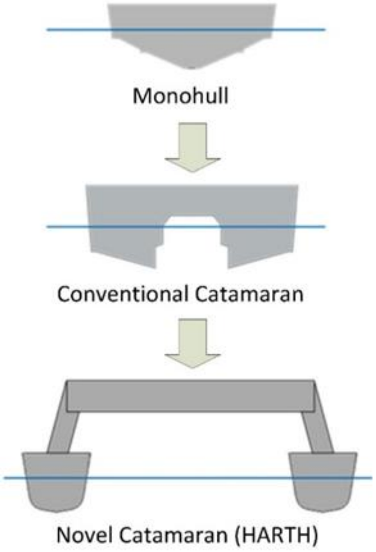
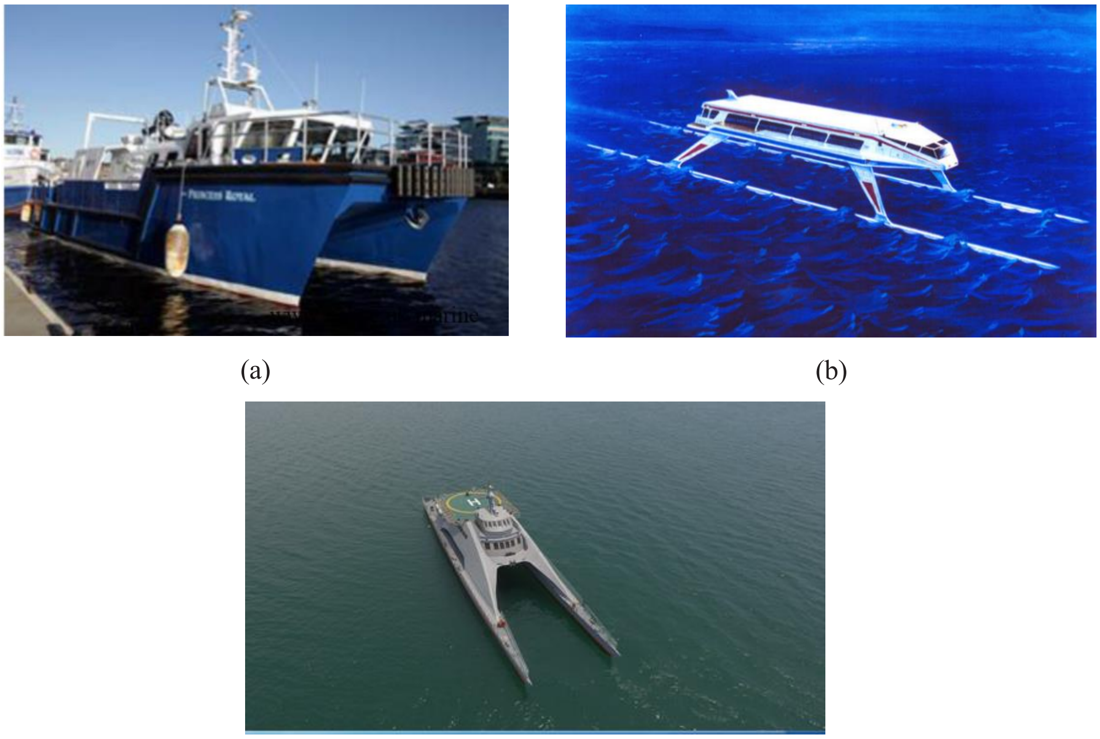


Figure 9: Developing of HARTH body form [33].

Figure 10 (a) shows a conventional catamaran [39] and figure 10(b) illustrated a schematic view of HARTH vessel [40] and figure 10 (c) shows a super slender catamaran that we called it HARTH vessel in this paper. Increasing the aspect ratio, decreases the drag forces of hull, and vessels can easily break the sea water during vessel operation. Also, in HARTH vessels, large distance between the pontoons leads to transverse stability of the vessel. Also HARTH, usually doesn't have any Centre bows. Because of high aspect ratio, the drag forces of these vessels is reduced in calm and harsh seas and these vessels can be more fuel efficient. So, HARTH concept can be a good choice for cruise and passenger ships. In addition, HARTH concept can reduce motion sickness in harsh sea sates and provide great ocean safety [33].



(a) (b)

(c)

Figure 10: RV princess Royal (Deep-V hull form catamaran) [39] (a); Conceptual Design of the HARTH Vessel [40]; super slender catamaran (HARTH) (C) [33].

The main dimension of the HARTH vessel is given at the table 1. Structural design of this novel vessel is partly based on direct calculation and marine standards like DNV, ABS and BV are used in designing of this vessel .we also used hydro-elastic method for calculating wave loads and used these data, in designing some critical points of this vessel[33].

Table 1: main dimension of HARTH vessel [33].

Specifications	Main ship (*m*)
Total length (m)	55
Length between two perpendiculars (m)	52.63
length of water line (m)	53.44
The draft from the base line (m)	1.46
Maximum Width (m)	14.1
Maximum width of the Draft in each demi-hull (m)	2.68

3.4 Buckling analysis of a mid-ship section of a HARTH vessel

According to high aspect ratio of this novel aluminum twin hull vessel, in compare with conventional catamaran vessel, this vessel prone to more buckling in the harsh seas, because of this, analyzing the buckling behavior of this vessel in intacted and damaged conditions is very important. For studying of buckling behavior of this structure, the mid-ship section of this hull structure that is the critical section of this structure regarding to loading exposed to this part, as a representative of structural buckling behavior of this vessel is chosen. Figure 11 shows the mid-ship section that is chosen for analyzing of this novel vessel [33].

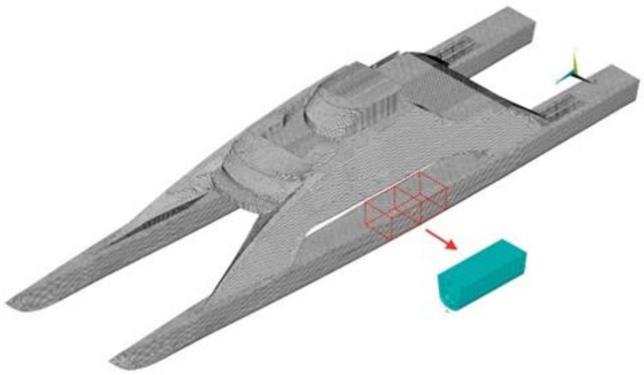
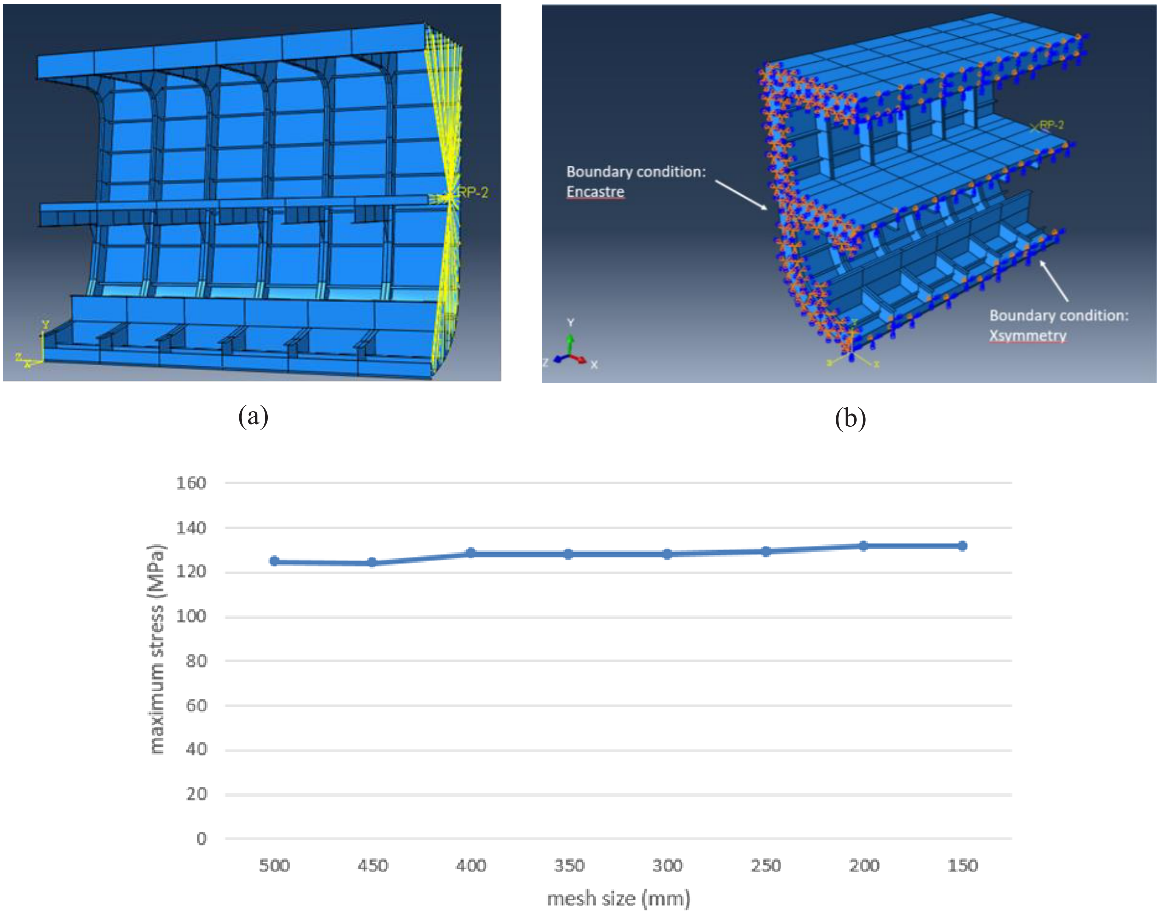


Figure 11: mid-ship section of the hull structure [33].

3.5. Defining the critical bending moment

In order to analyze the buckling behavior of vessel, two stages were considered. These stages were the linear and nonlinear buckling analysis. Since both the model and boundary condition were symmetric, only a quarter of mid-ship section was modeled [33].

Sheet's material was aluminum alloy 5083 with 215 MPa yielding stress and ultimate strength of 230 MPa. The stiffeners material was aluminum alloy 6082 with yielding stress of 230 MPa. Figure 12(a) shows a reference point that is positioned at one ends of the structure and all nodes at this end are coupled to the reference point. Bending moment is applied to this end. At the other end (figure 12(b)), fixed boundary conditions is used. This loading and boundary conditions produces pure bending moment along the structure length. For the boundary condition, a similar approach that were adopted by S.D. Benson et al. (2013) and E. Alfred Mohammed et al. (2016) is followed. Mohammed et al. presented a direct calculation methodology for the evaluation of the ultimate strength of a 10,000 TEU container ship by considering the combined effects of structural nonlinearities and steady state wave induced dynamic loads on a mid-ship section of a cargo hold. [41, 42]. For studying the effect of mesh size on the CAE model, as it shows in figure 12(c), the hull with different mesh sizes, was meshed(500mm ,450mm,400mm,350mm,300mm,250mm,200mm,150 mm) and the maximum of Von Mises stresses in the hull, as the result of same bending moment, was considered. In the all of the mesh sizes, the differences of maximum von Mises stresses in the hull, were below of 6% and finally the mesh size of 500 mm were selected for FEM simulations [33]. In figure 13 the material stress-strain curves for aluminum alloys 5083-H116 and 6082-T6 in the parent material and HAZ is shown [43].



(a)

(b)

(c)

Figure 12: reference point for applying the bending moment(a);boundary condition(b) ; mesh sensibility(c)[33].

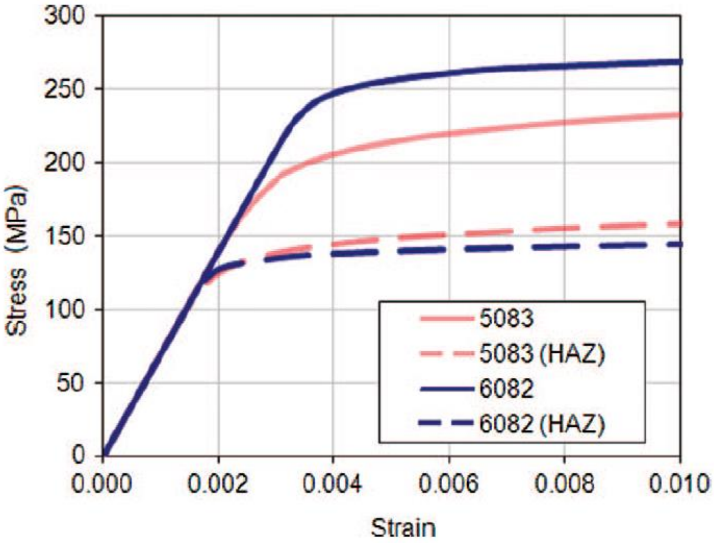


Figure 13: material stress-strain curves for aluminum alloys 5083-H116 and 6082-T6 [43].

Figure 14 shows the distributions of stress in linear analysis. As it shown ,the contributions of stresses in linear condition is centralizing on bottom and deck stiffeners and region around them.

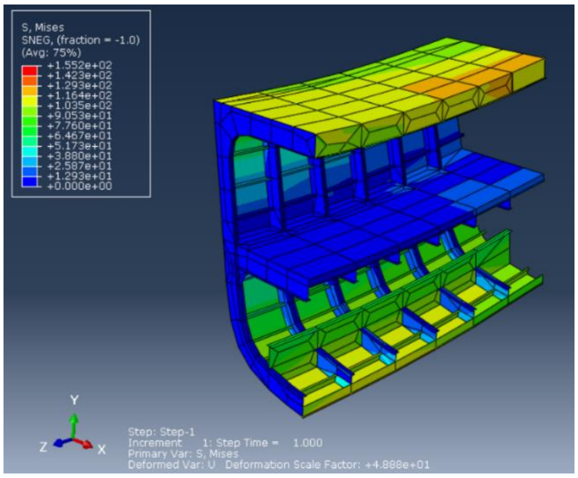


Figure 14: the distribution of stresses in liniar analysisof hull structure.

Because of high aspect ratio twin hull of this vessel, this kind of structure is prone to high level of cyclic loads because of this, fracture may start in hot spots under cyclic stresses .therefore it is possible and probable to a tearing and propagation of this failure mode. This kind of damage can reduce the structural strength and stability. Hydrostatic stability is not important here because of divided compartments of the hull; but structural aspect is important and should be studied.in this study a sensitivity analysis of the effect of location of such local failure on the global structural behavior is studied. In order to evaluate the effect of damage on the ship's hull strength, square damage with area of 0.6 sheet, was introduced in different locations. This ratio was chosen in order to obtain significant loss in strength. Figure 15 shows the different positions of damages in this study.

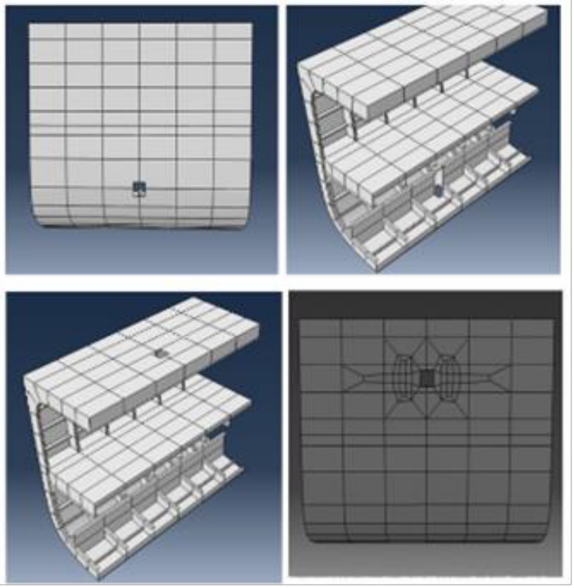
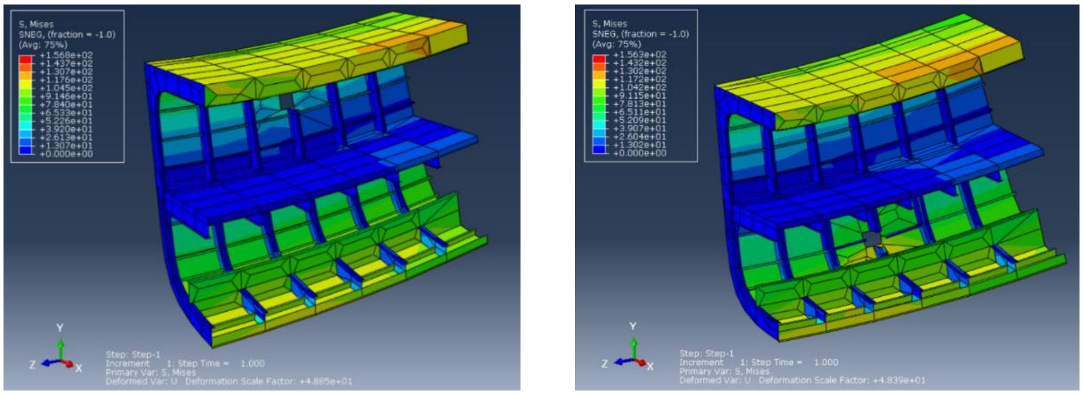


Figure 15: different positions of damages.

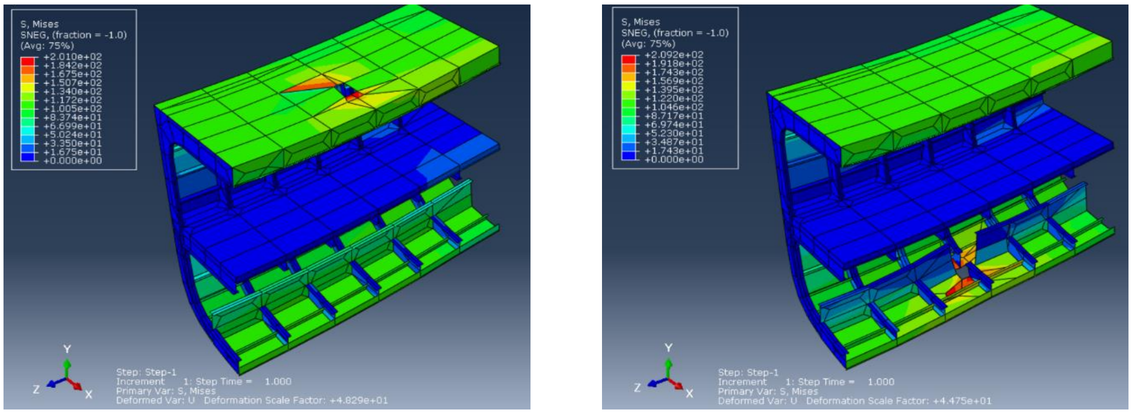
Figures 16(a&b) shows stress cotributions, when damaged area are on the side and side bottom of the hull structure.as it can be seen, these kinds of damaged area have less impacts on the global strength of the structure.



(a) (b)

Figure 16: distribution of stresses of side damage (a); distribution of stresses of side bottom damage (b).

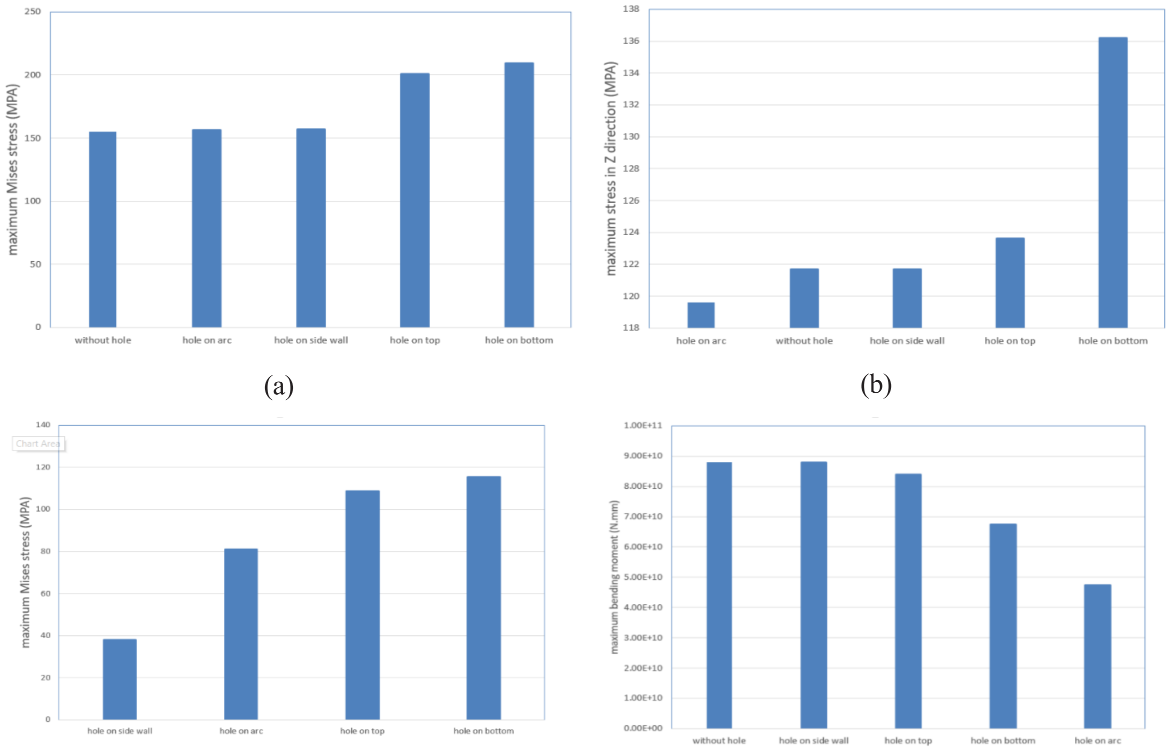
Also figures 17(a&b) shows the stress contributions when the damaged areas are on the deck and bottom area. As can be seen, in these conditions, decreasing the strength of the structue is noticeable and reduction of the structure strength is approximately more than 30% .



(a) (b)

Figure 17: distribution of stresses of deck damage (a); distribution of stresses of bottom damage (b).

Figure 18(a) and 18(b) shows the comparison of maximum Mises stresses on different damaged areas and maximum stress in z direction and in figure 18(c) the maximum mises stresses on a specific point(element 937 mm from center of damage area) is shown. As can be seen, with the same bending moments, damaged area on deck and bottom, have the larger impacts on structural strength and these kind of damages have to considered in structural design.Figure 18(d) shows the strength reduction of structure in different damaged locations.

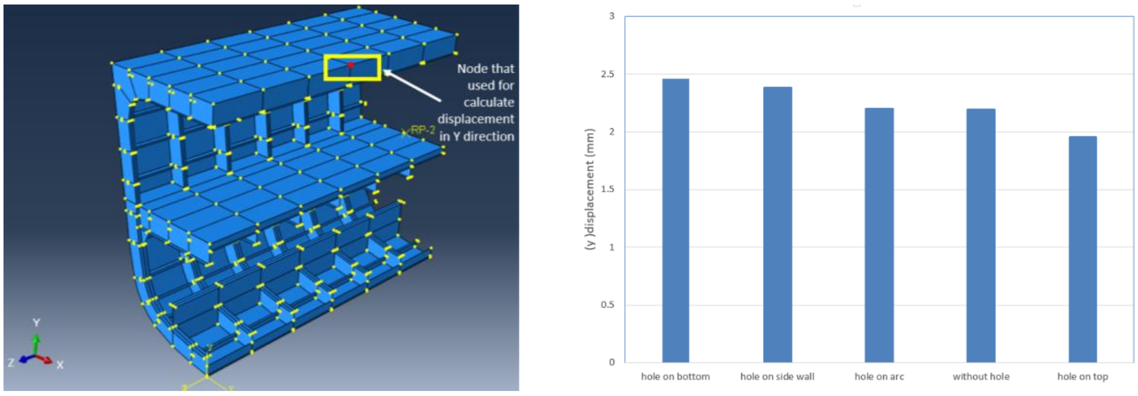


(a) (b)

(c) (d)

Figure 18: comparison of maximum Mises stress on different damaged locations (a); maximum stress in z direction (b); maximum mises stresses on element 937 mm from center of damage area (c); a strength reduction on different damaged locations (d).

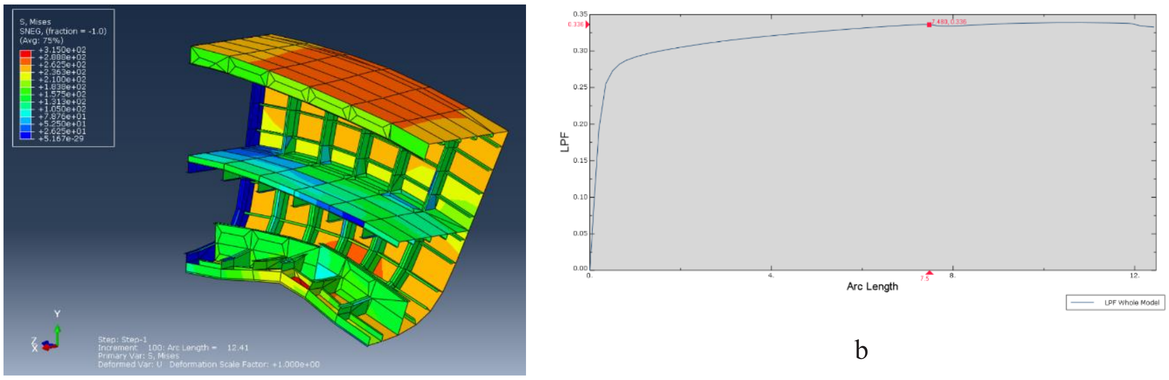
For considering the displacement in this structure, we have chosen one node of structure (figure 19(a)) and the displacement in Y direction is shown in figure 19(b).As can be seen, the maximum displacement is, when the damaged areas are on bottom structures.



a **b**

Figure 19: chosen node for calculating displacement in Y direction (a); the impact of damages on displacement.

For better understanding the structural behavior, non-linear analysis of this structure is carried out. Figure 20(a) shows non-linear analysis of structure, when damaged area is on bottom of structure; in figure 20(b) the LPF diagram (Load proportionality factor) related to this analysis is shown. Figure 21 shows maximum bending moments of the structure in non-linear analysis in intacted and damaged conditions and table 2 shows LPF in non-linear analysis of hull structure in these conditions.



b

a

Figure 20:non-linear analysis when the damaged area is on bottom of structure (a); LPF diagram (b).

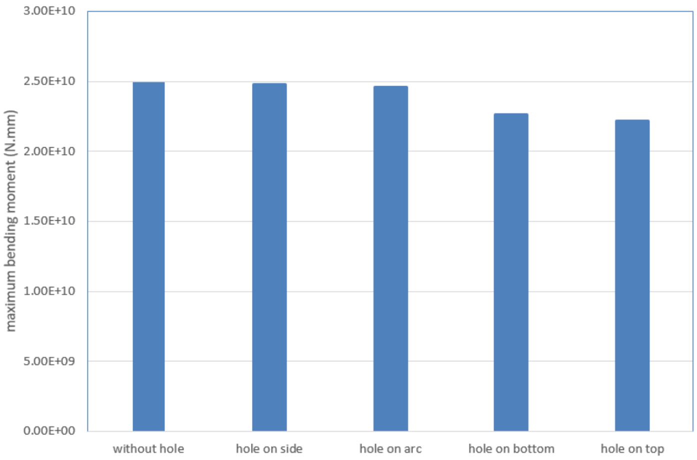


Figure 21: maximum bending moments in non-linear analysis.

Table 2: LPF in non-linear analysis

Damaged location	LPF
Without hole	0.284
Hole on side	0.282
Hole on top	0.264
Hole on bottom	0.336
Hole on arc	0.52

As can be seen in figure 20 and considering the linear analysis, buckling loads are near to each other in two condition of side damaged and intacted structure. According to table 2, LPF in both condition are near to each other. As it is shown in figure 28, buckling loads in intacted condition is 24951 KN.m and in side damaged condition is 24778

KN.m and as a result, damage in this region can create minimum impact on hull structural strength. Also as observed in linear analysis, damaged on deck area, have lower impact on structural strength in compare with damage on side; in non-linear analysis as it shown in table 2, LPF decreased from 0.28 to 0.26 , in compare with this condition; and finally as it is observed in linear analysis, the minimum structural strength is related to damage on bottom and side bottom(arc), but in non-linear analysis LPF coefficient related to these two conditions are high respectively and as a result, when these LPF multiplied to buckling loads in linear analysis, the distances between structural strength in intacted and damaged condition on side and deck area are less than is expected.

4. Conclusion and recommendation

Damage occurrence in metal sheet, will result in loss of strength, regardless of damage's area or shape. Stress concentration in areas close to damaged area, caused to decrease the strength. The location of damage, has a significant impact on residual strength of aluminum sheets. In case the damage is close to edges and far from center of sheet, strength of aluminum plates is minimum. This is especially noticed that, when damaged area is close to longitudinal edges and parallel to the axis of loading. This is direct result of stresses distribution in sheet. During buckling out of plate, the displacement is not the same for elements inside the plate. This displacement is maximum for elements in central regions while elements in vicinity of edges have no considerable movement outside the plane and hence undergo maximum stress. The strength of sheet is highly depends on strength of this areas and loss of strength is considerable, if this effective width is damaged. As observed in linear analysis, the strength of sheet is depends on the area of damage to the area of sheet. As this fraction grows, strength of sheet decreases considerably. On the other hand, there was no relation between the shape of damage and strength. Yet the nonlinear analysis provides a more accurate criterion on the effect of shape of damage on sheet's strength. It was observed that the strength of sheet is independent from shape of damage if its width, perpendicular to axis of loading direction, remains constant. For a mid-ship section of a novel aluminum twin hull structure, with the comparison of maximum Mises stress on different damaged areas and maximum stress in z direction with the same bending moments, it can be observed that, damaged area on deck and bottom have the larger impacts on structural strength and these kind of damages have to considered in structural design.also the maximum displacement in this structure is, when the damaged areas are on the bottom of the hull.

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