Effect of uniform corrosion on mechanical behavior of E690 high-strength steel lattice corrugated panel in marine environment: a finite element analysis

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Abstract

The quasi-static compression, three-point bending and low-speed impact behavior of E690 high-strength steel lattice corrugated sandwich panels after corrosion in a marine environment were simulated by a non-linear finite element method. The uniform corrosion model was used to calculate the effects of different levels and duration of corrosion on the bearing capacity and energy absorption of an E690 panel. The results show that the corrosion of the outer panel has the least influence on the decrease of the mechanical properties; the structure’s mechanical properties are greatly reduced by the inner panel and core corrosion, and a new deformation pattern could be observed. Considering the influence of corrosion duration, the mechanical performance ranges from bad to good: outer + inner > inner > outer. Furthermore, the difference becomes more obvious with longer corrosion times, indicating that necessary corrosion protection measures should be taken to protect the panel from corrosion in marine environment, especially for the internal part of the panel.

1. Introduction

The design and development of lightweight and multi-functional marine structures have become an important challenge in many fields of research including materials, mechanics and mechanical engineering [1–5]. As a typical periodic lattice structure, a corrugated metal sandwich panel has many advantages, such as relatively simple fabrication, high rigidity and lightweight, and has been widely used in engineering. A lot of research has focused on the performance, design and manufacturing of high-strength steel corrugated panels [6, 7]. Due to the frequent occurrence of malignant damage accidents and shortening of the service life of offshore structures caused by corrosion, it is necessary to study the mechanical behavior of high-strength steel corrugated panels in marine environment. The corrosion behavior of high-strength steel in marine environment has been systematically studied [8–11], but there is little study on corrosion behavior of high-strength steel corrugated panel and in particular its influence on mechanical properties.

The corrosion mechanism of high-strength steel in marine environment have been well discussed [12–15]. Wang et al [16] found that high-strength pipeline steel in simulated marine environment mainly showed uniform corrosion, and the situ 3D microscope was applied to study the corrosion morphology. Chen et al [17] studied the corrosion behavior of high-strength weathering steel in simulated marine atmospheric environment, the results showed that the circumferential immersion corrosion test has an excellent correlation with the marine atmospheric corrosion process, and the uniform corrosion rate is subject to power exponential law with the extension of immersion time. Lu et al [18] studied the corrosion evolution of E690 high-strength steel in simulated marine environment under potentiostatic anodic polarization, and the result showed that the initiated pitting corrosion could transform to uniform corrosion at OCP.

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Therefore, the uniform corrosion of high-strength steel in marine environment would mainly lead to the material thickness reduction, thus affecting the mechanical properties of the structure. Uniform corrosion may also have a significant effect on the overall mechanical properties of the panel, and changes in the corrosive environment may also influence the corrosion rate and mechanism. The corrosion rate of carbon steel sandwich panel in marine environment has been investigated by EU Sandwich project [19], but the related mechanical degeneration properties have not been touched. Jerovica et al [20, 21] studied the corrosion rate and bending resistance of a panel after 2 years immersion, but other mechanical properties such as energy absorption and impact resistance were not studied. This may still be considered of importance, as other works have shown that the mechanical properties of corrugated panel such as compression, bending and impact resistance show significantly different performance with variation of panel and core size [22, 23].

In order to make up for the lack study of corrosion behavior of high-strength steel lattice corrugated sandwich plate structure in offshore engineering. Therefore, for the present study E690 high-strength steel lattice corrugated sandwich panel was chosen as the research object, and the effect of uniform corrosion on the degradation of mechanical properties of the panel was simulated by finite element method. The quasi-static compression, three-point bending and low-speed impact property of panels corroded at different locations, corrosion degree and corrosion time are investigated, and the degradation of load bearing and energy absorption are discussed. These results can not only help to understand the impact of uniform corrosion on degradation of mechanical properties of high-strength steel corrugated panel in corrosive environments, but also provide a sound theoretical basis for the selection, optimization and safety evaluation of this kind of marine structures.

2. Details on the finite element model

2.1. Material and structure

In this work, E690 high-strength marine structure steel was used for simulation [24], the chemical composition are C 0.095, Si 0.21, Mn 1.47, S 0.0012, Al 0.0236, V 0.033, Cr 0.45, Ni 0.32, Mo 0.46, B 0.0018, Ti 0.015 and Fe balance (in wt-%). The yield stress is 739 MPa and the tensile stress is 799 MPa. The parameters of lattice corrugated sandwich in this study refers to Yan et al [25], as show in figure 1. The angle $\alpha$ is 45°; the height of the core $H$ is 17 mm; the width of the sample is 20 mm; the thickness of the core $t$ is 2 mm; and the thickness of the upper and lower panel $h$ is 2 mm for the quasi-static compression and low-speed impact specimen, and 3 mm for the three-point bending specimen. The relative density of the corrugated core is equal to the volume fraction [26]:

$$\bar{\rho} = \frac{t/H}{s/H + \cos \alpha}$$  \hspace{1cm} (1)

The connection of lattice corrugated sandwich in this study is the welding. It can be prepared by shearing plate, bending, welding and other technological steps. The plate surface and core are all made of E690 high-strength steel. The proposed preparation process is to cut the E690 steel plate through line cutting to the required size of the panel and core, the put the core on the bending machine to bend into a corrugated core structure with an angle of 90°, and then connect the plate surface and the corrugated core through laser welding.

2.2. Corrosion mode

The loss of material by electrochemical degradation is the most direct way to define corrosion [26–29]. In this study, uniform corrosion is regarded as the thickness reduction of structure sections in severe marine corrosion environment. Due to the complexity of the lattice corrugated panel, three different situations are considered: (1) good internal corrosion protection, corrosion only occurs on the outer surface of the panel, the thickness reduction by corrosion is considered for 0.5, 1 and 1.5 mm, respectively; (2) the external of panel is well
protected while the internal is not, corrosion occurs within the panel. In this case, the thickness reduction of the inner panel and core is 0.5, 1 and 1.5 mm, respectively; (3) the inner and outer panel corrode simultaneously and at the same rate, the section thickness reduction for the single surface is 0.25, 0.5 and 0.75 mm respectively, which is 0.5, 1 and 1.5 mm for the whole panel surface reduction.

The uniform corrosion rate of carbon steel in a marine environment typically follows an exponential law [30, 31]:

\[ r = r_A \times t^{r_B} \]  

where \( r \) represents the corrosion depth (in \( \mu m \)) after \( t \) years, \( r_A \) is the first year corrosion rate, and \( r_B \) is an index obtained by experimental regression analysis. The value of \( r_A \) and \( r_B \) is 70.6 and 0.79 respectively in marine environment [31]. Thus, the corrosion time to reach the above assumed depth can be calculated, the thickness reduction of 0.25, 0.5, 0.75, 1, and 1.5 mm corresponds to 5.0, 11.9, 19.9, 28.7, and 47.9 years in actual marine service condition.

2.3. Simulation method
The quasi-static compression, three-point bending and low-speed impact performance of the E690 panel was simulated by ABAQUS explicit finite element commercial software. The material type selected is consistent with the experiment, and the isotropic elastic-plastic solid constitutive model is adopted. Since the corrosion products of E690 steel are relatively loose and most of them will fall off and the mechanical properties of the adherent corrosion products could be ignored compared with the un-corroded steel [14], so we would not consider the influence of corroded material here. The base material parameters are as follows: density \( \rho_s \) is 7850 kg m\(^{-3}\), Young’s modulus \( E_s \) is 210 GPa, Poisson’s ratio \( \nu \) is 0.3 and yield strength \( \sigma_s \) is 739 MPa. The von Mises yield criterion and the J2 flow rule are utilized in the modeling. With this, the overall and local mechanical behavior of the panel can be simulated.

2.3.1. Quasi-static compression
The quasi-static compression specimen consists of three complete cells (figure 1). The real stress-strain curve is adopted in the simulation without considering the strain rate effect. The lower end pressure plate is fixed, the upper end pressure plate is compressed downward by 15 mm, and the compression speed is 1 mm ms\(^{-1}\). The structure is divided by S4R units with a grid size of 1 mm \( \times \) 1 mm. The upper and lower pressure plates are divided by R3D4 units, and the mesh size is 1.2 mm \( \times \) 1.2 mm. The corrugated core is ideally connected to the panel, and the friction coefficient of the overall structure is 0.3. The density strain of this structure can be as high as 70% [25], in order to obtain the complete compression process, the compression strain of each specimen is exceeding 70%.

The area under the stress-strain curve of the quasi-static compression represents the energy absorption capacity of the material. The total energy absorption (TEA) can be defined as \( W_c \):
where $s$ is the compression stress, $e$ is the compression strain and the upper limit of strain integration $\varepsilon$ is 0.5. The specific energy absorption (SEA) of the panel is defined as $W_m$:

$$W_m = \frac{W_v}{(\rho_s \rho_r)}$$

(4)

where $\rho$ is the relative density in equation (1), $\rho_s$ is the density of E690 steel and $W_v$ is the total energy absorption in equation (3).

2.3.2. Three-point bending

The three-point bending simulation is divided into two types, the transverse bending and the longitudinal bending specimen, as shown in figures 2(a) and (b), respectively. For the transverse bending specimen, the width is 40 mm and length is 312 mm corresponding to 9 core cells. Since the welded joint (top of the corrugation)
between the corrugated core and the panel is the point with the strongest bearing capacity, then the load is applied to the joint during the three-point bending simulation, as shown in figure 2(a). For the longitudinal bending specimen, the width is 76 mm, including 2 core cells. The specimen size diagram and the loading method are shown in figure 2(b).

2.3.3. Low-speed impact
The low-speed impact simulation specimen contains three complete cells (figure 1). The principle of a free falling body is adopted in the simulation. The J-C model is adopted and the dynamic parameter C is 0.021 [32]. The lower end of the pressure plate is fixed, and the upper end simulates a 50 kg drop hammer with an initial velocity of 10 m s⁻¹.

3. Results and discussion

3.1. Quasi-static compression
Figure 3 shows the loading-displacement curve of quasi-static compression and the deformation mode when the compression reaches 70%. The intensity and total energy absorption parameters are shown in table 1. It can be seen from figure 3(a) that the peak load does not change significantly with the increase of the corrosion depth in the outer panel, all being around 126 kN; the total energy absorption (TEA) decreases slightly with the increase of corrosion depth; and the specific energy absorption (SEA) of the 1.5 mm corroded outer panel increases by about 23% than that of the original. The peak load decreased significantly with the increase of the corrosion depth in the inner part of the panel (see figure 3(b)), its reduction is about 80.9% when the corrosion depth reaches 1.5 mm; the TEA also decreases sharply to about 92.9% at a corrosion depth of 1.5 mm; the SEA of 0.5, 1.0, and 1.5 mm respectively.

It can be seen from the deformation pattern at a compression of 70% (figures 3(a1)–(c1)) that an obvious plastic hinge can be generated at the center of the corrugated plate core, the evolution process of this plastic hinge dominates the deformation of the panel, and the deformation increases with the increase of the compression strain. At the same time, there will be a plastic hinge near the end of the corrugated core unit, but it is very small compared with that at the center, so its influence can be ignored [22, 33].

Figure 4 shows the comparison of quasi-static compression mechanical properties of E690 panel at different depths of uniform corrosion. It can be seen that for the same corrosion depth, the degree of structural mass loss and the peak load reduction is: outer + inner > inner > outer (figures 4(a) and (b)); the TEA reduction is: outer + inner ≈ inner > outer (figure 4(c)); and the SEA reduction is: inner > outer + inner > outer (figure 4(e)). It can be seen from the above analysis that for the same corrosion depth, uniform corrosion has little effect on the quasi-static bearing capacity and energy absorption efficiency when only the outer surface is corroded, however, once the inner part of the panel is corroded, the mechanical properties of the structure are significantly reduced.

The corrosion of inner and outer of panel is the most severe case if the service time is considered. For example, the time for single surface thickness reduction of 0.5 mm is about 11.9 years by using equation (1); but in case 3 where the inner and outer panels are all corroded simultaneously, the corrosion depth is 1 mm and it can be equivalent to 28.7 years of exposure. It can be seen from figures 4(d) and (f) that TEA and SEA could be

| Corrosion part | Corrosion depth, (mm) | Mass, (g) | Peak load, (kN) | \( W_c \), (kJ) | \( W_m \), (J/g) |
|----------------|----------------------|----------|----------------|----------------|----------------|
| Comparison     | 0                    | 120.65   | 126.6          | 978.3          | 8108.6         |
| Outer          | 0.5                  | 111.71   | 126.3          | 969.5          | 8678.3         |
|                | 1.0                  | 102.76   | 126.2          | 936.1          | 9109.5         |
|                | 1.5                  | 93.81    | 126.1          | 935.3          | 9970.2         |
| Inner          | 0.5                  | 99.44    | 93.5           | 640.1          | 6437.4         |
|                | 1.0                  | 78.23    | 56.7           | 301.1          | 3848.5         |
|                | 1.5                  | 57.01    | 24.6           | 69.7           | 1222.5         |
| Outer + Inner  | 0.5                  | 90.49    | 93.6           | 636.0          | 7027.8         |
|                | 1.0                  | 60.21    | 57.7           | 298.7          | 4960.5         |
|                | 1.5                  | 30.16    | 20.2           | 82.2           | 2724.6         |
reduced sharply if the service time is 11.9 years, and the level of decrease is in the following order: outer + inner > inner > outer. Moreover, with the extension of service time, the difference becomes more significant, indicating that the overall corrosion seriously damages the mechanical properties of the panel and necessary corrosion protection measures would be badly needed.

3.2. Three-point bending

3.2.1. Transverse loading mode

Figure 5 depicts the transverse three-point bending curve, the initial failure mode and final damage morphology when the compression reaches 17 mm. Under transverse three-point bending load, the panel surface mainly bears a bending moment, while the core mainly bears shear stress. The mass loss of the panel decreases linearly while the bending stiffness and peak load decrease with progressive corrosion. When the outer panel is corroded...
by 1.5 mm, the bending stiffness and peak load decrease by 35.2% and 45.7% respectively, and the initial failure mode is yield of the panel (Table 2). The peak load and bending stiffness decrease with the increase of corrosion depth when the inner panel and core is corroded, which decrease by 60.6% and 63.0% respectively when the corrosion depth reaches 1.5 mm, and the initial failure mode changes from panel yield to core buckling. The peak load and bending stiffness decrease with the increase of corrosion depth when both inner and outer of panel is corroded, which decrease by 46.9 and 63.0% respectively when the overall corrosion depth reaches 1.5 mm, and the initial failure mode changes from panel yield to core buckling.

### Table 2. The transverse three-point bending mechanical properties of E690 panel after different depths of corrosion.

| Corrosion part | Corrosion depth, (mm) | Mass,(g)    | Bending stiffness, (N mm\(^{-1}\)) | Peak load, (kN) | Initial failure mode |
|----------------|-----------------------|-------------|----------------------------------|----------------|----------------------|
| Outer          | 0                     | 469.41      | 5881                             | 14.0           | Face yielding        |
|                | 0.5                   | 442.52      | 5195                             | 13.6           | Face yielding        |
|                | 1.0                   | 415.73      | 4578                             | 10.4           | Face yielding        |
|                | 1.5                   | 388.81      | 3811                             | 7.6            | Face yielding        |
| Inner          | 0.5                   | 405.76      | 5055                             | 11.0           | Face yielding        |
|                | 1.0                   | 342.12      | 4307                             | 9.2            | Face yielding        |
|                | 1.5                   | 271.33      | 3118                             | 5.2            | Core buckling        |
| Outer+Inner    | 0.5                   | 378.91      | 4547                             | 11.1           | Face yielding        |
|                | 1.0                   | 288.42      | 3376                             | 9.2            | Face yielding        |
|                | 1.5                   | 197.94      | 2319                             | 5.2            | Core buckling        |
Figure 6 shows the comparison of transverse three-point bending mechanical properties of an E690 panel under different uniform corrosion conditions. For the same corrosion depth, the degree of mass loss and the bending stiffness reduction is: outer + inner > inner > outer (see figures 6(a) and (b)); and the peak load reduction is: outer + inner ≈ inner > outer (see figure 6(c)). Therefore, only outer surface corrosion has relatively little influence on the bending stiffness and peak load of the structure, however, it will be significantly reduced once the inner panel is corroded. The impact of corrosion time on peak load is depicted in figure 6(d). It can be seen that the peak load reduction degree after service under marine corrosive conditions for 11.9 years is outer + inner > inner > outer, which is significantly different from the thickness reduction shown in figure 6(c), and the difference is more obvious for longer corrosion times.

3.2.2. Longitudinal loading mode
Figure 7 shows the longitudinal three-point bending curve, the initial failure mode and final damage morphology when the compression reaches 17 mm, the surface of panel mainly bears a bending moment while the core mainly bears shear stress. The bending stiffness and peak load in the longitudinal loading case are higher than that for the transverse loading case under the same condition. The mass loss decreases linearly when the outer panel is corroded, while the bending stiffness and peak load decrease with the increase of corrosion depth. When the outer panel is corroded by 1.5 mm, the bending stiffness and peak load decrease by 32.5 and 47.6% respectively, and the initial failure mode is yield of panel (table 3). The peak load and bending stiffness decrease with the increase of corrosion degree when the inner panel and core are corroded, which decreases by 54.2 and 55.2% respectively when the thickness reduction reaches 1.5 mm, and the initial failure mode is gradually transformed from panel yield to core yield. The peak load and bending stiffness decrease with the increase of corrosion degree when all panel are corroded, which decrease by 63.8 and 72.0% respectively when the corrosion degree reaches 1.5 mm, and the initial failure mode changes from panel yield to panel and core yield.
It can be seen from the above data that both the transverse and longitudinal bending resistance of E690 panel decreases with the increase of the corrosion degree of the outer surface, while the peak load and SEA of the quasi-static compression are not affected by the outer panel corrosion. However, the thickness of the panel has a very
significant influence on the bending resistance under the action of three-point bending load, and obvious anisotropy could be observed, those findings are in accordance with some other studies [25, 34]. It can be seen that the corrosion degree has great influence on the deformation pattern of E690 panel. When the external panel is seriously corroded, the main failure mode is the surface of panel failure, such as the face yielding; and when the internal is corroded, the main failure mode is in the core. The relative degree of corrosion between inner and outer surface and core dominates the failure mode of E690 panel under three-point bending load.

The comparison of longitudinal three-point bending mechanical properties of E690 panel under different uniform corrosion conditions is shown in Figure 8. The degree of mass loss and the bending stiffness reduction is: outer + inner > inner > outer (see figures 7(a) and (b)); and the peak load reduction is: outer + inner > inner ≈ outer (see figure 7(c)) which is significantly different from that of the transverse loading. It can be concluded that only single surface corrosion has relatively little effect on the mechanical performance of the panel, but it will be significantly reduced once the whole panel is corroded. The impact of corrosion time on peak load is depicted in figure 8(d), the peak load reduction degree after service for 11.9 years is: outer + inner > inner ≈ outer, and the difference is more obvious with the increase of corrosion time.

3.3. Low-speed impact
The loading-displacement curve and the deformation mode when the compression reaches 70% of low-speed impact is shown in figure 9 and the mechanical parameters are shown in table 4. It can be seen from figure 9(a) that the peak load does not change significantly, being all around 140 kN; the TEA decreases slightly with the increase of corrosion depth; and the SEA when corroded for 1.5 mm increases by about 42.8%. The peak load decreased significantly with increasing corrosion depth of the inner panel (see figure 9(b)), its reduction being about 78.5% when the corrosion depth reaches 1.5 mm; the TEA also decreases sharply with the increase of corrosion depth, it decreases by about 81.6% at a corrosion reduction of 1.5 mm; and the SEA of 0.5, 1.0 and

Figure 8. The longitudinal three-point bending mechanical properties of E690 panel after different depth of uniform corrosion: (a) structure mass, (b) bending stiffness and (c) peak load and different corrosion time: (d) peak load.
Figure 9. Loading-displacement curve (a)–(c) and the deformation pattern when impact deformation reaches 70% \((a_1, b_1, c_1)\) of E690 panel after different depth of uniform corrosion: \((a, a_1)\) outer layer, \((b, b_1)\) inner layer and \((c, c_1)\) outer and inner layer.

Table 4. The Low-speed impact mechanical properties of E690 panel after different depth of uniform corrosion.

| Corrosion part | Corrosion depth, (mm) | Mass,(g) | Peak load,(kN) | W\(_r\),(kJ) | W\(_m\),(J g\(^{-1}\)) |
|----------------|-----------------------|----------|---------------|-------------|-----------------|
| Comparison     | 0                     | 120.65   | 140.9         | 1025.4      | 8498.9          |
| Outer          | 0.5                   | 111.71   | 131.4         | 956.0       | 8558.1          |
|                | 1.0                   | 102.76   | 131.2         | 953.9       | 9283.3          |
|                | 1.5                   | 93.81    | 131.0         | 950.5       | 10132.6         |
| Inner          | 0.5                   | 99.44    | 98.1          | 664.4       | 6681.0          |
|                | 1.0                   | 78.23    | 71.9          | 358.3       | 4580.1          |
|                | 1.5                   | 57.01    | 30.3          | 82.6        | 1447.2          |
| Outer+Inner    | 0.5                   | 90.49    | 98.2          | 647.6       | 7156.1          |
|                | 1.0                   | 60.21    | 66.4          | 344.3       | 5718.1          |
|                | 1.5                   | 30.16    | 32.1          | 88.0        | 2917.4          |
1.5 mm corroded specimens decreases by 21.4, 46.1 and 83.1%, respectively. The peak load decreased significantly with the increase of the overall corrosion depth (see figure 9(c)), the peak load decreases by about 77.3% when the corrosion depth reached 1.5 mm; the TEA decreases about 91.4% after thickness reduction reaches 1.5 mm; the SEA decreases by 15.8, 32.7 and 65.7% when the corrosion depth is 0.5, 1.0, and 1.5 mm respectively.

The low-speed impact mechanical properties as a function of corrosion depth and time are shown in figure 10. It can be seen that for the same corrosion depth, the peak load and TEA reduction is: outer + inner ≈ inner > outer (figures 10(a) and (c)); and the SEA reduction is: inner > outer + inner > outer (figure 10(e)). Uniform corrosion shows to have little effect on the low-speed impact capacity and energy absorption efficiency when only the outer surface is corroded, however, once the inner panel is corroded, the
mechanical properties of the structure are obviously reduced. The corrosion time on the mechanical properties of the panel is shown in figures 4 (d), (d) and (f). It can be seen that peak load, TEA and SEA reduce sharply with extended service times and the decrease degree is: outer + inner > inner > outer. Combining the previous results of quasi-static compression and three-point bending, it can be considered necessary to protect the E690 panel from corrosion in marine environment, especially the inner part of the structure.

4. Conclusions

(1) Uniform corrosion has little effect on the quasi-static and low-speed impact bearing capacity and energy absorption efficiency of the E690 panel when only the outer surface is corroded, nevertheless, once the inner of panel is corroded, the mechanical property of the structure is significantly reduced.

(2) The bending stiffness and peak load in a longitudinal loading case are greater than that for the transverse loading case. The bending stiffness and peak load decrease with the increase of corrosion. When the inner and outer panel are all corrode simultaneously and the corrosion degree reaches 1.5 mm, the initial failure mode changes from panel yield to core buckling and core yield for transverse and longitudinal loading.

(3) The corrosion duration plays an important role in the evolution of mechanical performance of the E690 panel, i.e. it reduces with prolonged service times and the order of the level of decrease is: outer + inner > inner > outer. For relatively long service times, corrosion protective measures should be taken to protect the structure from corrosion in marine environment especially the inner part of the structure.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflicts of Interest

The authors declare no conflict of interest.

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