

Residual Ultimate Strength of Axially Compressed Tube after Collision or Corrosion

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Residual Ultimate Strength of Axially Compressed Tube after Collision or Corrosion

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Chapter 1. Introduction

In this chapter, the research background and the organization of this thesis are given. In Section 1.1, a literature review is presented and the gaps in previous research are pointed out. In Section 1.2, the procedures of this thesis are illustrated. In Section 1.3, the organization of this thesis is stated.

1.1 Overview and background

With the transfer of oil and gas industry from land to ocean, the development of offshore structures and related techniques is rapid in recent decades. Among all kinds of offshore structures, the jacket platforms are first applied and used most widely. The followings are the advantages of the jacket platforms.

- The design and manufacture techniques are mature;
- The economical efficiency is outstanding especially in shallow water regions (general below 200m);
- Adaptability for various environment situations;
- The structure stability and safety characteristics is approved.

As the technique of design and manufacture improved and widely explosion in all over the world, the oil and gas production in offshore fields plays an important role in the energy resource supply. Although the leg tubes of jacket platforms are carefully treated from the design stage to the maintenance, accidents still occurred in the past. Several noteworthy offshore accidents summarized by Wang ^[1] and Bhandari et al ^[2] are listed in Table 1.1. Offshore platform is a system of many facilities and complicated procedures, including drilling, storage and transportation and other installations. Hence, if one leg fails, it will cause severe consequence. The damage might only be estimated to be the direct loss. The additional economic losses also contain the fees to repair or replace the broken part of the system, to tear down the offshore structure if the damage is unrepairable defective as well as the costs and efforts to deal with the potential environment pollution caused by the leaked oil.

Table 1.1 Several noteworthy offshore catastrophes ^[1, 2]

Accident	Year	Fatalities	Cost due to damage
Umm Said Qatar	April 1977	3 died	\$ 179 million
Ekofish Norway	March 1980	123 died	
Mexico Pipe Leaking	November 198	650 died	\$ 29 million
Sleipner Norway	August 1991		£ 160 million
Piper Alpha North Sea	July 1998	167 died	\$ 1.2 billion
Sinking of Erika	December 1999	8 died	
Roncador Brazil	March 2001	2 died	\$ 515 million

Besides, the negative influences of such accidents also injure the confidence of offshore engineers and restrict the development of offshore techniques. Therefore, to minimize the possibility of accidents is a primary target for both the scholars and practitioners in this field.

The present research focuses on the substructure of jacket platforms which is the supporting construction. Usually a substructure is made up by a series of mild steel tube members by welding. Firstly, the potential loadings of the jacket platforms are shown in Fig. 1.1. As shown in this figure, the main load for the tube members of the substructures are axial loading and bending. The leg tubes are components of the substructure, so the function of leg tubes is to bear the axial compressive load. However, the jacket platform is fixed to the sea bed and it is difficult to move, so the repairing cost is high. Therefore, the residual ultimate strength of damaged tube is worthy to be investigated.

Therefore the central target in the present research is to investigate the axial compressive residual ultimate strength of circular tubes after damaged. The FEM method is applied in this research. With the help of numerical simulation, the residual ultimate strength of tubes is investigated.

There are two kinds of damage, which are introduced into the tube members in this research. They are accident load and time depending load. As for the accident load, it is described in Handbook of Offshore Engineering ^[3] which includes loads from residual events that may be caused by accidents such as vessel impact, dropped object impact, fire and blast and unusual environmental conditions. Magnitudes of these loads are obtained from a global risk assessment study or based on past experience and code requirements. Platform is generally designed against

these loads with safety factors. And API ^[4] rules are recommended to be referred in the design stage of jacket platforms.

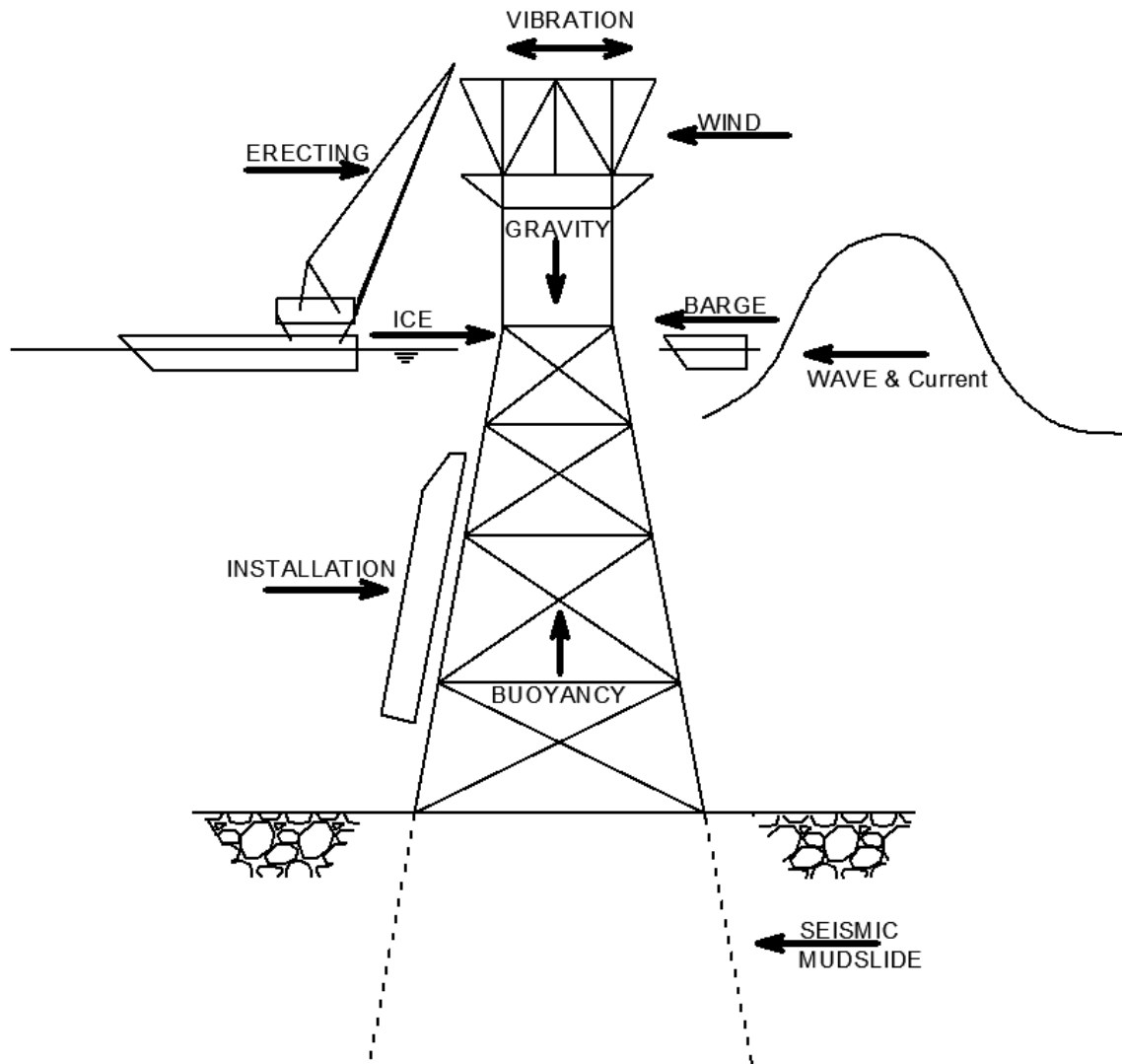


Fig. 1.1 Types of loads acting on a fixed offshore platform

The time depending effect is the corrosion which is a normal phenomenon to be taken into consideration in ship and offshore structures design. Since mild steel is widely used to build constructions, corrosion effect leads to the material loss as time passes. The shell thickness reduction is the main results due to corrosion.

The above mentioned two effects both influence the axial compressive ultimate strength of circular tube members that act as the supporting structures of jacket platforms.

The tube members used in offshore structures as the substructures are in large size ^[5-12]. The scantling range is shown as follows,

Length, L	16~40m;
Diameter, D	2.0~3.5m;
Thickness, t	25~55mm.

And the properties of mild steel will be shown in Table 2.1 in Section 2.2.1.

The critical ultimate strength of the tubes with the D/t less than 100 is almost the yield stress of the material according to Guide to stability design criteria for metal structures ^[14] as shown in Fig. 1.2.

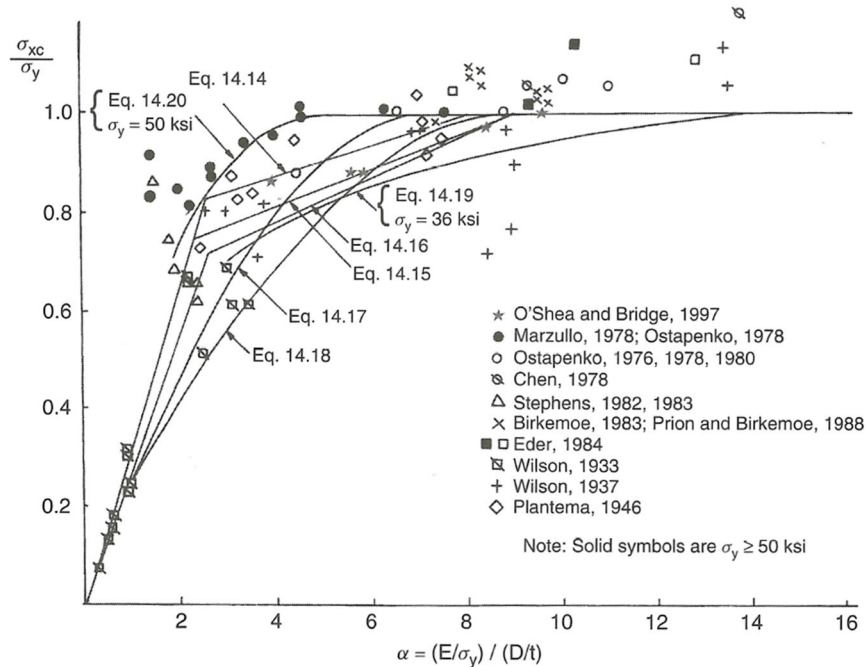


Fig. 1.2 Inelastic buckling equations and data for axially loaded cylinders plotted by Ziemian et al ^[14]

The criteria of judgement on whether the loading capacity of tube members is acceptable or not is according to API rules ^[4]. The allowable axial compressive stress is calculated based on the API rules ^[4] as follows. The API rules ^[4] could provide a reference to determine the residual ultimate strength of damaged tube is acceptable or not.

The allowable axial compressive stress, σ_a , should be determined from the following formulas. For tubes with a D/t ratio equal to or less than 60:

$$\sigma_a = \frac{\left[1 - \frac{(Kl/r)^2}{2C_c^2}\right] \sigma_y}{5/3 + \frac{3(Kl/r)}{8C_c} - \frac{(Kl/r)^3}{8C_c^3}} \quad \text{for } Kl/r < C_c \quad (1.1-1)$$

$$\sigma_a = \frac{12\pi^2 E}{23(Kl/r)^2} \quad \text{for } Kl/r \geq C_c \quad (1.1-2)$$

Where, $C_c = \left(\frac{2\pi^2 E}{\sigma_y}\right)^{\frac{1}{2}}$,

σ_y = yield strength, MPa,

E = Young's Modulus of elasticity, MPa,

K = effective length factor, Section 3.3.1d, (equals to 1.0 in this research)

l = unbraced length, m,

r = radius of gyration, m.

For tubes with a D/t ratio is greater than 60 and less than 300, with wall thickness $t > 6$ mm, both the elastic (σ_{xe}) and inelastic local buckling stress (σ_{xc}) due to axial compression should be determined from Equation (1.1-3) and Equation (1.1-4). Overall column buckling should be determined by substituting the critical local buckling stress (σ_{xe} or σ_{xc} , whichever is smaller) for σ_y in Equation (1.1-1) and in the equation for C_c .

Elastic Local Buckling Stress:

$$\sigma_{xe} = 2CEt/D \quad (1.1-3)$$

Where, C = critical elastic buckling coefficient (the theoretical value of C is 0.6),

D = outside diameter, m,
 t = wall thickness, m.

Inelastic Local Buckling Stress:

$$\left. \begin{aligned} \sigma_{xc} &= \sigma_y \times \left[1.64 - 0.23(D/t)^{1/4} \right] \leq \sigma_{xe} \\ \sigma_{xc} &= \sigma_y \quad \text{for } (D/t) \leq 60 \end{aligned} \right\} \quad (1.1-4)$$

It is a normal sense that the existence of geometrical initial imperfection leads to the reduction of the ultimate strength of shell structures. Yudo and Yoshikawa ^[15] investigated the effect of initial imperfection on the bending capacity of tubes, in that research the initial imperfection mode is shown in Fig. 1.3.

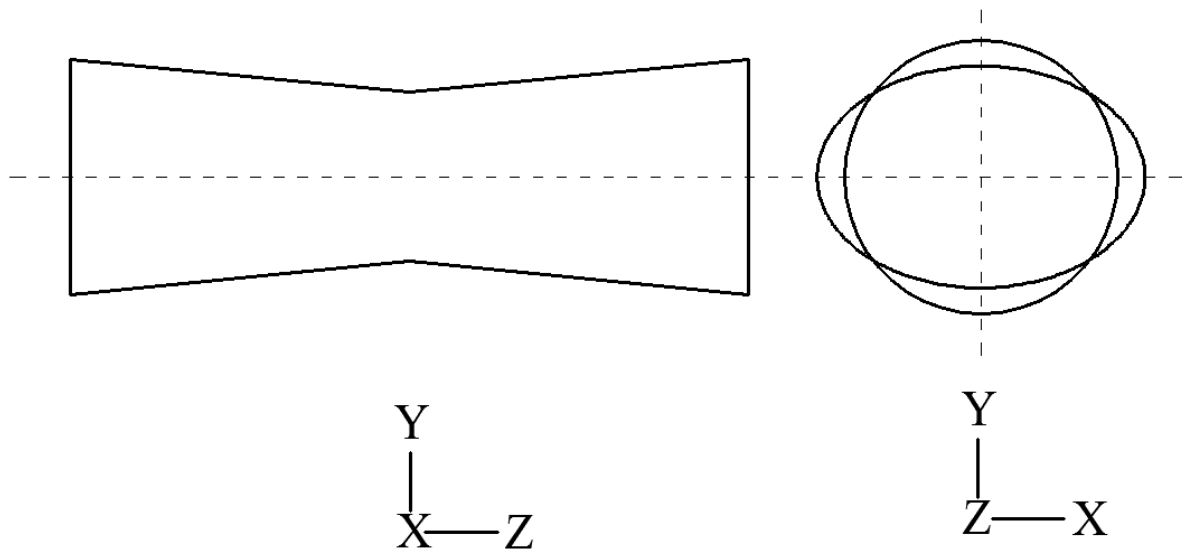


Fig. 1.3 The initial imperfection of oval mode by Yudo and Yoshikawa ^[15]

Teng et al. ^[16] investigated the behaviors of FRP-circular tubes. And Fraldi and Guarracino ^[17] tested the geometrical imperfection of cold-formed tubes, and found that $n=2$ and 3 in Equation (1.2) is the most normal situations. However for the circular tubes under axial compression, the most severe case of initial deflection is uniform symmetrical buckling mode in the circumferential direction and elastic buckling mode in axial direction.

$$w = w_0 \sin\left(\frac{\pi y}{L}\right) \cos n\theta \quad (1.2)$$

In the field of ship collision with offshore structures, Amdahl ^[18], Hu ^[19, 20] and Watan ^[6] all investigated the collision force between ship and offshore structures. However the residual ultimate strength of tube members after such kind of collision has seldom been studied before. So this important characteristic is studied in this thesis.

The effect of corrosion is a rather complicated phenomenon on ship and offshore structures. In order to avoid the material loss in marine systems, coating is the basic and effective measurement to protect the steel from corrosion. Whereas, the lifetime of coating is limited compared to the lifetime of marine structures. Wang ^[21], Melchers ^[22, 23], Garbatov ^[24] and Paik ^[25] measured and investigated corrosion effect on ships with the exposure period. The statistics data of corrosion level and corrosion depth shows that it has a very large variable range. That means the corrosion situation varies very much from one ship to another, from one location of the ship to other locations. It is very difficult to predict the corrosion effect quite accurate in the lifetime of marine structures. So, the maximum pit depth is applied for safety side, generally.

Two types of corrosion are usually considered. One is the general corrosion which is treated as the uniform thickness reduction of the plate and shell. The other is the pit corrosion, this kind of corrosion is more localized. Nakai ^[26] observed the shape of pit corrosion on hold frames of 12, 14 and 20 years-old bulk carriers and a 22 years-old oil tanker. And the relationship between pit diameter and depth is shown in Fig. 1.4. He found that the pit shape is a circular cone and the ratio of the diameter to the depth is in the range between 8 to 1 and 10 to 1 in bulk carriers, and the ratio is in the range between 4 to 1 and 6 to 1 in oil tankers. That provide a reference for actual pit shapes.

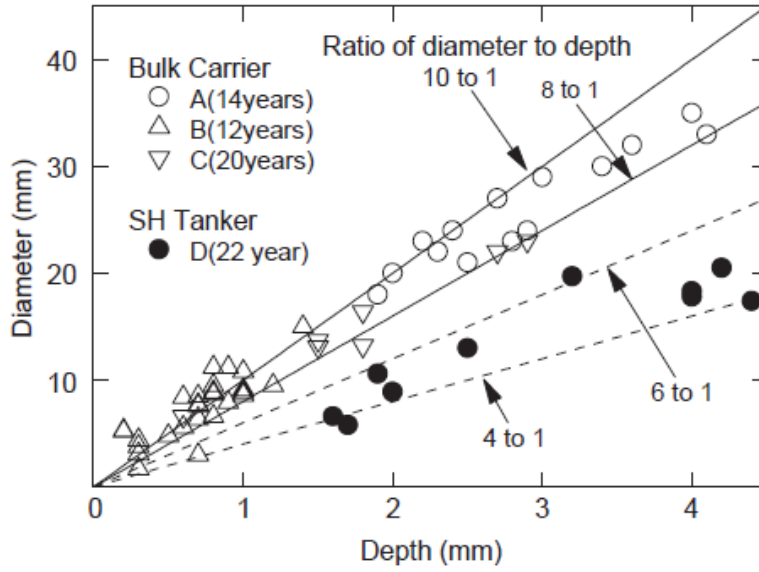


Fig. 1.4 The relationship between corroded pit diameter and depth observed by Nakai ^[26]

In terms of the modelling of corroded plates in FEM calculation models, the majority of the researches, solid elements of small size are used, such as Ahmmad ^[27]. Shell elements model is also applied, however, pits are arranged symmetrically on both surfaces of the plate, such as Paik et al ^[28] and Wang et al ^[29]. Zhang ^[30] applied shell elements to model the corroded stiffened plate only on one side of the plate. It is assumed that, pitting corrosion almost occurred to overall the plate. It is concluded that the *DOP* (the degree of pit corrosion intensity defined as the ratio of pitted area to the whole surface area) affected on the ultimate strength of corroded plate. However, the dominant parameter to influence on the residual ultimate strength of pit corroded plate might be the residual cross section area.

The shell thickness geometrical variation and material property is investigated by Shu ^[31], Guedes ^[32], Vhanmane ^[33] and Gaspar ^[34]. The variation ratio of standard deviation to the mean value (design value) of thickness is 5%. That is 8% of material yield stress. And the distribution of thickness and Young's modulus both obeys normal distribution. For yield stress, the distribution obeys the log-normal distribution. The stochastic model for geometrical parameters and material properties by Gaspar ^[34] is shown in Table 1.2 and Table 1.3, respectively.

Table 1.2 Stochastic model for geometrical parameters by Gaspar ^[34]

Variable	Distribution	Mean value, μ	COV, σ/μ
l (m)	Normal	Design value	0.05
t (mm)	Normal	Design value	0.05

cf.) σ is the standard derivation.

Table 1.3 Stochastic model for material properties by Gaspar ^[34]

Variable	Material	Distribution	Mean value, μ	COV, σ/μ
σ_y (N/mm ²)	Steel, NS	Log-Normal	269	0.08
	Steel, HS		348	0.06
E (N/mm ²)	Steel, NS&HS	Log-Normal	206000	0.10

cf.) Design values for normal strength steel (NS): $\sigma_y=235\text{N/mm}^2$, 5th percentile;
 $E=206000\text{ N/mm}^2$, mean value.

Design values for high strength steel (HS): $\sigma_y=315\text{N/mm}^2$, 5th percentile;
 $E=206000\text{ N/mm}^2$, mean value.

The physical parameters are not unchangeable values. Every parameter has its own variation range. According to Gaspar et al ^[34], the effects of the variation ranges of tube scantlings, namely length L , diameter D and shell thickness t , and material properties, Young's modulus E and yield stress σ_y , are investigated in this thesis.

1.2 The procedures of present research

The purpose of this research is to investigate the residual ultimate strength of damaged tube members. These tube members are used to form the substructures of jacket platforms. The axial compressive loading capacity of tubes is the basic to guarantee of the safety of platforms. Two kinds of damage are mainly discussed here. One is the lateral collision of supply vessels, a dynamic accidental load. The other is pit corrosion, a static time-depending load, since pit corrosion is a more complicated type than general corrosion which is treated to be the reduction of thickness.

In the research of collision effect on tube residual ultimate strength, numerical simulation is performed applying LS-Dyna, which is a non-linear FEM software widely adapted in collision and explosion. The residual ultimate strength of damaged tubes is calculated. Referring the API rules, the acceptable value of the residual ultimate strength of damaged tubes is determined.

In the research of corrosion effect on tube residual ultimate strength, MSC.Marc is applied to calculate static calculations. MSC.Marc is applied for static analysis. The method to model the corroded area of plate structure with shell elements is investigated. This method shall provide accurate results and time efficient. By applying this method, the residual ultimate strength of corroded tubes is studied using large size of shell elements.

To assess the safety of damaged tubes in the design and maintenance, it is required to easily predict the residual ultimate strength. Simplified formulae are also derived to predict the residual ultimate strength considering the FEA results.

The probability study on the collision effect is also required to be performed, considering the variation of material yield stress and shell thickness. The colliding mass and velocity variations are important factors in collision effect research. In corrosion effect, the timespan between two inspections based on the predictions of the strength reduction and corrosion depth is investigated.

1.3 Organization of present thesis

In Chapter 2, the residual ultimate strength of tube members after lateral impact is studied. A series of numerical simulation is performed in LS-Dyna. Parametric study is accomplished by changing the tube scantling and impact energy. Also the effect of impact shape and impact position are also investigated. Based on the residual ultimate calculation results. The parameter, λ , is proposed to represent the relative anti-impact ability of tubes. A non-dimension formula is derived to describe the relationship between residual ultimate strength of damaged tube and this parameter. Then the API rules are referred to estimate the critical acceptable damaged situation. Final, the effect of variable material physical properties is investigated.

In Chapter 3, the residual ultimate strength of pit corroded plates is studied as a preliminary step for investigation of the residual ultimate strength of pit corroded tubes. Numerical simulations are performed by MSC.Marc. Firstly, a method is proposed to model corroded area of shell structures with shell elements. It is proved that this method is time efficient with reasonable accuracy. Secondly, the residual ultimate strength of pit corroded plate is investigated by applying the above method. A typical size of the plates used in marine structures is adapted. The crucial parameter to influence on the residual ultimate strength of pit corroded plate is examined. A formula is derived to describe the residual ultimate strength of corroded plate.

In Chapter 4, the residual ultimate strength of pit corroded tube is investigated. Tube scantling parameter study is performed. The relationship between the residual ultimate strength of pit corroded tube and the corrosion level is obtained. Moreover, the effect of variable material physical properties is investigated as well.

In Chapter 5, the engineering suggestions are carried out. For the collision effect on tubes, probability of failure of collided damaged tubes is investigated. With the application of the simplified formula proposed in Chapter 2, Monte Carlo method is used to point out the safety criteria value of impact energy. Based on that, a suggestion of the approaching velocity of supply vessels is proposed. For the corrosion effect on tube members, the relationship between residual ultimate strength and corrosion rate is investigated with the help of the simplified formula proposed in Chapter 4. Thereby, the approach of maintenance is suggested.

In Chapter 6, the researches of present paper are summarized and concluded. And future works are discussed.

Chapter 2. Residual Ultimate Strength of Circular Tube after Lateral Collision

2.1 Introduction

Circular steel tubes have been widely applied as the basic element of substructure of fixed offshore structures, such as jacket platforms. The main function of supporting tube is to bear axial loading, especially axial compressive load. As a fixed offshore structure, jacket platforms may suffer from many kinds of accidental load, for example, the lateral impact by supply vessel and floating objects. These accidents will influence the load capacity of supporting tube. Such kind of impact will lead to plastic deformation on tube members. As a result, the ultimate strength of tubes will decrease compared to that of intact ones.

This chapter focuses on the assessment of ultimate strength of the tube structure after collision impact. Ship collision is a dynamic phenomenon with high energy. Minorsky ^[35] first summarized 26 events, and provided formulae describing the relationship between the damage volume and energy dissipation. This method had been widely used in this area by many researchers.

Amdahl ^[18] and Wierzbicki and Suh ^[36] both investigated the deformation model of circular tubes under lateral impact. However, the lateral load in Amdahl's research was applied by a rigid plate parallel to the tube axis. While the load in Wierzbicki and Suh's ^[36] research was applied by a line impact onto one section of the tube. Then they derived the relationship of lateral deformation of the tube and energy dissipated in collision. But the above scenario that a supply vessel impacts laterally to the supporting tube of jacket platforms is not the most dangerous of collision cases. In the other hand, it seems to be more dangerous that the bow structure collides to the tube members. Nevertheless, this kind of collision cases have not been investigated by them.

Based on Amdahl and Wierzbicki and Suh researches, Hu ^[19, 20] investigated the relationship between colliding force and indentation using analytical, numerical and experimental methods. However, the residual ultimate strength after collision was not investigated.

Other works ^[37-39] focused on the failure mode of the tubes under axial compression, and in those researches the tubes were relatively short ones, with the L/D ratio around 1~10. Meanwhile the L/D ratio for jacket platforms is larger than that, about 40. Where L and D is the length and diameter of the tube member.

Watan ^[6] investigated the collision between the side structure of supply vessel and the jacket platform tube. In his work, collision velocity, collision position along the tube axis and tube geometric parameter have been varied. Finally, the relationship among the collision force, energy and impact indentation have been derived. The scenario of the collision between jacket platforms and supply vessels is bow impact. He concentrated on the collision force rather than the ultimate strength of the tube after collision. In his FEM model, the tube thicknesses were 30, 40 and 50mm, the element length was 100mm, and the ratio of element length to thickness was 2~3.3.

The shape of ship bow has been illustrated by several researchers based on real ship structures. Shown by Storheim and Amdahl ^[7], the actual collision is within 11~14MJ range, directed by NORSOK rules. The bulbous radius along the centerline was approximately 2m and 1m along the stringer deck in the middle of the bulbous.

In Travanca and Hao ^[8] research, the height of this vessel is 6.3m and deadweight is 3000ton. The diameter of bulbous bow is about 2m. And the tube length is ranging about 25m, with diameters of 1.28-1.70m.

Yu and Amdahl ^[5] also analyzed the tubular members of offshore structures impacted by ships. The length, diameter and thickness is around 20m, 1.5m and varying from 30 to 50mm. The bulbous diameter is approximately 2.0m.

Bela et al ^[9] investigated the collision between the Offshore Wind Turbine and Offshore Supply Vessel. The yield stress of the material for the circular column structure of Offshore Wind Turbine was around 250MPa. The vessels were 3000 and 5000ton of DWT. Collision velocity range was from 1 to 5m/s. In his calculation results, after the impact of ship with the velocity of 5m/s, the tube had almost lost the bearing capacity under the axial load.

And then Bela et al ^[9] performed additional numerical simulation to investigate the energy dissipation of the above scenarios with deformable striking ship model. With the high collision velocity about 5m/s, the offshore structure absorbed up to 80% of the total energy.

Most of previous researches focused on predicting the collision force, the interaction with ship structure and the energy dissipation. They concerned more about the collision event itself. In the present study, the main objective is the residual load carrying capacity of the offshore tubes after impact. In this chapter, the ultimate strength of damaged circular tubes in axial direction was investigated. The residual axial ultimate strength of damaged tube after collision was mainly discussed. That was compared to the ultimate strength of intact tubes.

In order to make a decision on whether to repair or replace the members or not, it is crucial to know the residual strength of the tubes. After being damaged by lateral impact, the simply supported tubes will definitely loss a certain extent of load carrying capacity under uniform axial compression.

Therefore, in this chapter, the relationship between the residual ultimate strength of the damaged circular tube by collision and the energy dissipation due to lateral impact is investigated. The influences of several parameters, such as the length, diameter and thickness of the tube and the impact energy, on the reduction of ultimate strength are investigated.

A series of calculations by changing the scantling of tube and colliding conditions is first undertaken to obtain the reduction rate of the residual ultimate strength of damaged tube to that of intact one. In these calculations, the location of damage was assumed to be at the middle span of the tube. Secondly, a simplified formula was derived to predict the residual ultimate strength of the circular tube. And then, by changing the collision position, the applicability of the

proposed formula was examined. By comparing with the allowable compressive stress proposed in API rules ^[4], the critical damage of tube due to collision impact to be repaired is proposed. Finally, the applicability of proposed formula is investigated by considering the variation range of tube thickness and material properties.

2.2 Basic Case

The purpose of this chapter is to investigate the residual ultimate strength of the tubes that collided and deformed. Firstly, the nonlinear FEM analysis was performed to investigate the residual deformation that was caused by collision. Next, the residual ultimate strength of the deformed tube under axial compressive force was examined. All numerical calculations in this chapter were computed utilizing the nonlinear FEM software LS-DYNA, which is widely used in the research field of ship collision and very good accuracy is approved by many previous researchers, such as Watan ^[6], Yu and Amdahl ^[5] and Bela et al ^[9]. The calculation model and calculation method will be shown below.

2.2.1 Dimension and material of tube

The dimensions of tubes are chosen according to actual size of ship and structure referring the study of Watan ^[6], Travanca and Hao ^[8] and Yu and Amdahl ^[5]. The length, diameter and thickness of legs used in jackets substructures in their studies are in the range of 16~40m, 2.0~3.5m and 25~55mm respectively.

So the Basic case of this chapter was decided as that the length (L), diameter (D) and thickness (t) of the tube is 30m, 2.5m and 40mm, respectively. And the impact mass (M) is 1000ton with the initial velocity (V_0) of 5m/s.

The material properties of the tubes are shown in Table 2.1, where the mild steel with the $\sigma_Y=235\text{MPa}$ was selected because of the wide application of this kind of steel in offshore structures.

Table 2.1 Material property of tube members

Items	Parameters
Yield stress	235MPa
Mass density	7850kg/m ³
Young's modulus	2.1×10 ⁵ MPa
Poisson's ratio	0.3
Strain rate parameter, C	40.4 s ⁻¹ [13]
Strain rate parameter, P	5.0 [13]

cf.) C and P are the parameters in Cowper-Symonds equation: $\frac{\sigma_d}{\sigma_s} = 1 + \left(\frac{\dot{\epsilon}}{C} \right)^{1/P}$;

σ_d and σ_s are the dynamic and static stress, respectively.

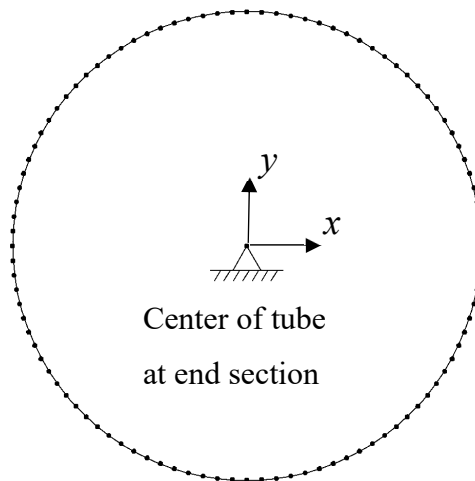
2.2.2 Striking load

As stated in introduction, up to 80% of the total impact energy was absorbed by the collided offshore structure in collision of ship. The bow structure is stronger than the side part of the supply vessel. And the stiffeners are much more concentrated in the bulbous bow than the upper structure. For most ship the extending distance of bulbous bow is almost the same as the upper structure. As a results, the most severe situation is that the tube members is struck by the ship bulbous bow. From a conservative point of view, the colliding object was assumed to be rigid. Based on the real structures applied in previous researches Storheim and Amdahl [7], Trtavance and Hao [8], Yu and Amdahl [5] and Bela et al [9], a sphere with the diameter of 2.0m is applied as the colliding body in this chapter.

Although the cruising speed of supply vessel is about 15~20knot, the velocity could slow down below 10 knot when collision might occur. Then, the impact velocity of 5m/s (about 10knot) is selected as Basic case. Large deadweight of striking vessel leads to severe deformation to the tubes, such as Bela et al [9] stated. Because the residual ultimate strength of damaged tube cannot be expected in such large amount of impact energy cases, these cases are excluded in this chapter. In order to avoid the extreme situations, the impact mass was selected to be around 1000ton.

2.2.3 Boundary condition

For a tube used as jacket leg, other leg tube and brace tube are connected to it on both ends. The bending rigidity of brace members is much smaller at that of leg tube. Therefore at the ends of a tube, the rotation displacements can easily occur. On the other hand the translated displacements are almost constrained. Then, the simply supported conditions were selected to be the boundary conditions at both end of tube as shown in Fig. 2.1. In order to apply the simply supported conditions at both ends of tube, all nodes at each end of tube were connected to the center point of each end section with rigid elements, and the displacements in x and y directions were constrained at both center points. Both cross sections of tube ends were assumed not to deform during the whole process, since neither the collision nor the compression would not influence on the deformation of both ends cross section.



At the center points of both tube end, the displacements in x and y directions are constrained. All nodes at each end of tube are connected to the center point of each end section with rigid elements.

Fig. 2.1 Modeling of boundary condition at both ends

2.2.4 Meshing division

The tube was divided into 100 elements in the circumferential direction with the four nodes Belytschko-Tsay^[42] shell element, and the sizes of elements in tube circumferential and axial directions are closed to each other. The element size is 78.5×78.5 mm for the Basic case, and the ratio of element length to thickness was nearly 2.0 as the thickness of tube is 40 mm. In order to verify the validity of this element size, a case with smaller element size of 40×40 mm is calculated. Almost the same results are obtained.

2.2.5 Loading procedure

There are two loading stages in the simulations in this chapter. The first stage is the lateral impact by a rigid body to the tube at the mid span of the tube, and the second stage is the axial compression of the tube. Then, the calculation time of first stage is set to 0~5.0s, and that of second stage is set to 5.0 ~12.0s.

The initial configuration of tube before lateral impact and the deformation after impact are shown in Fig. 2.2. The circular ones in the figures show the colliding rigid body. The rigid body has an initial velocity of 5.0m/s and a mass of 1000ton in the Basic case. The ends of the deformed tube rotated freely after collision.

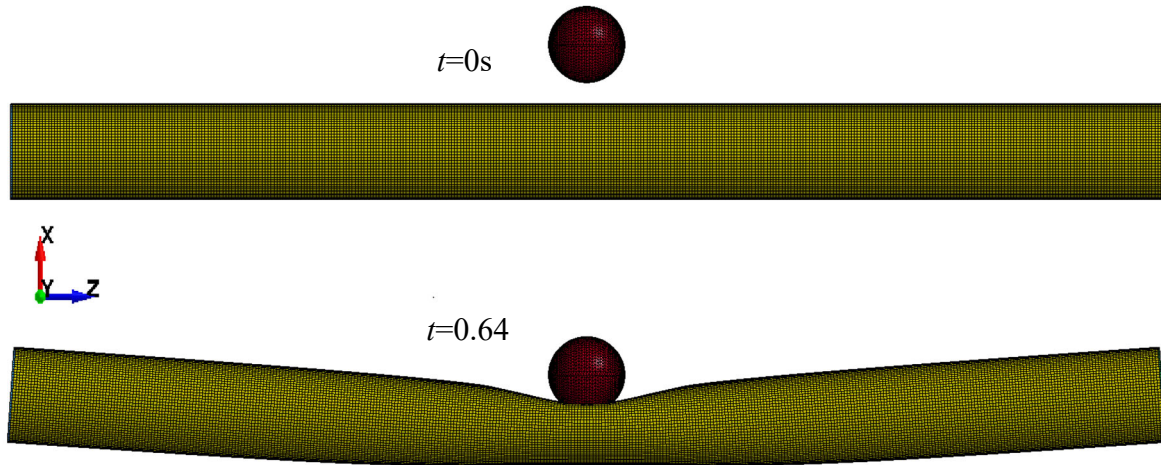


Fig. 2.2 Tube and rigid sphere before and after lateral impact in the first stage of the Basic case

The typical deformations of tube under axial compression in the second stage are shown in Fig. 2.3. In this case the center point of left side is fixed in z direction while the that of right side is moving towards left with the velocity of 0.02m/s (the length of the tube is 30m). When the tube suffers the axial compression, the cross section at the middle span of the tube will deform in the same direction as well as the residual plastic deformation caused by lateral impact.

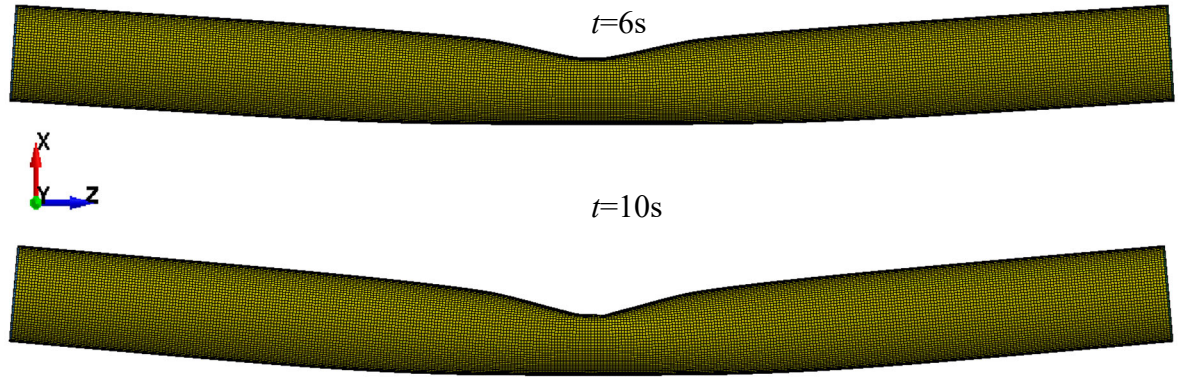


Fig. 2.3 Tube deformation under axial compression in the second stage of the Basic case

In addition, the above velocity of 0.02m/s was confirmed to be sufficiently low speed to represent the quasi-static behavior of axially compressed tube by the parametric calculation of changing velocity.

2.2.5.1 Calculation of residual deformation in collision

Fig. 2.4 shows the side view of contact area between the collided tube and the colliding sphere. In this figure, the center of contact area is the front point of the tube. The deformation in the vicinity of the front point is separated into two modes. One is the global deformation of tube as a column. The other is the local deformation at contact section. In this chapter, the separation of these two deformations is estimated from the numerical results.

Since the tube is simply supported at both ends, and the collision position is the middle span of the tube, the section of both ends will share a unique angle of rotation θ_y while the tube is impacted by the rigid sphere as shown in Fig. 2.5. Then, the global displacement δ_g can be evaluated by multiplying this rotational angle to the half of tube length, that is $\delta_g = 1/2L \times \tan\theta_y$. Where, L is the length of tube. The displacement of front point consists of global deformation and local deformation. Then, when δ_t is defined as the total displacement of the front point, local displacement δ_l could be calculated as $\delta_t - \delta_g$. The results will be shown later in Section 3.1.1. The time history of reaction force F_B at bottom end during the first stage is shown later, in Fig. 2.6.

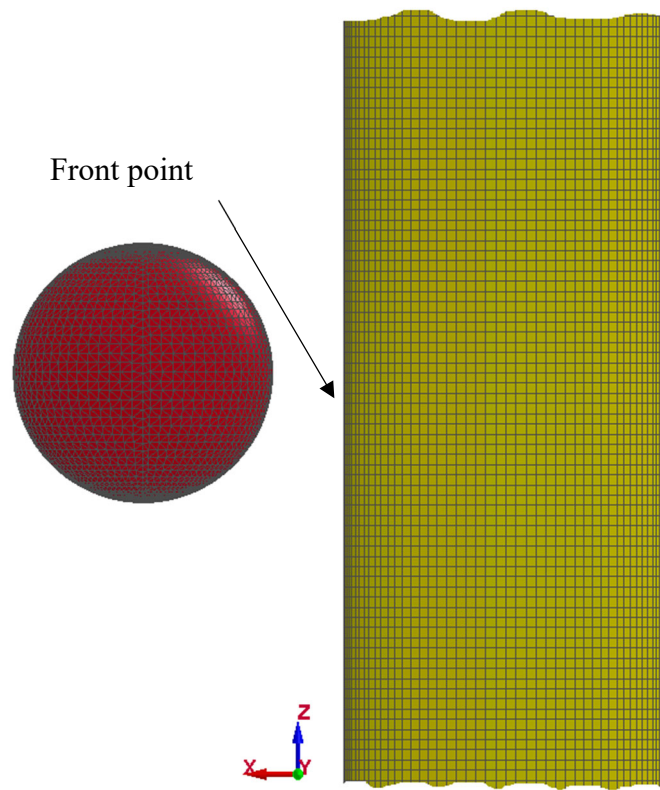
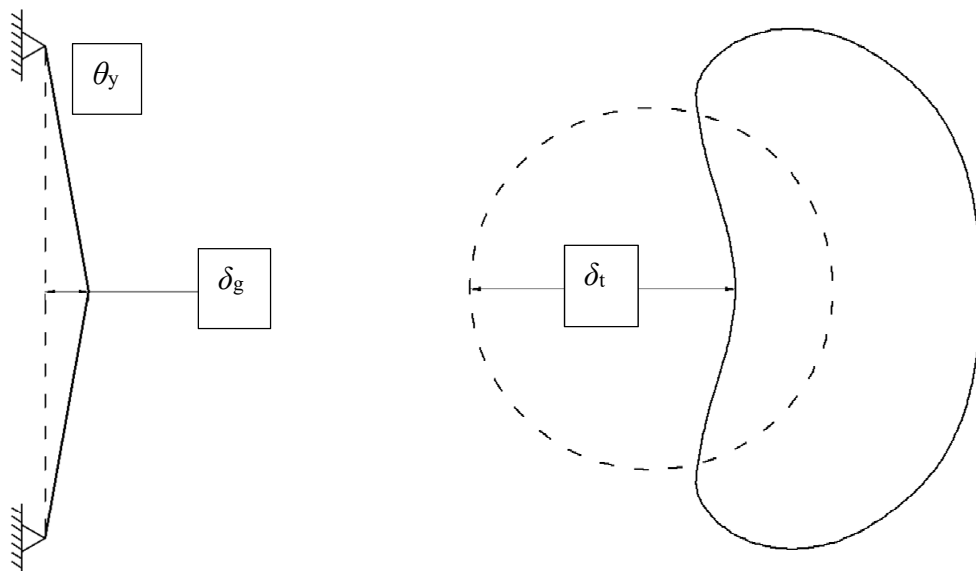


Fig. 2.4 Side view of contact area



(a) Overall deformation of tube (b) Cross sectional deformation at contact point

Fig. 2.5 Schematic view of deformation

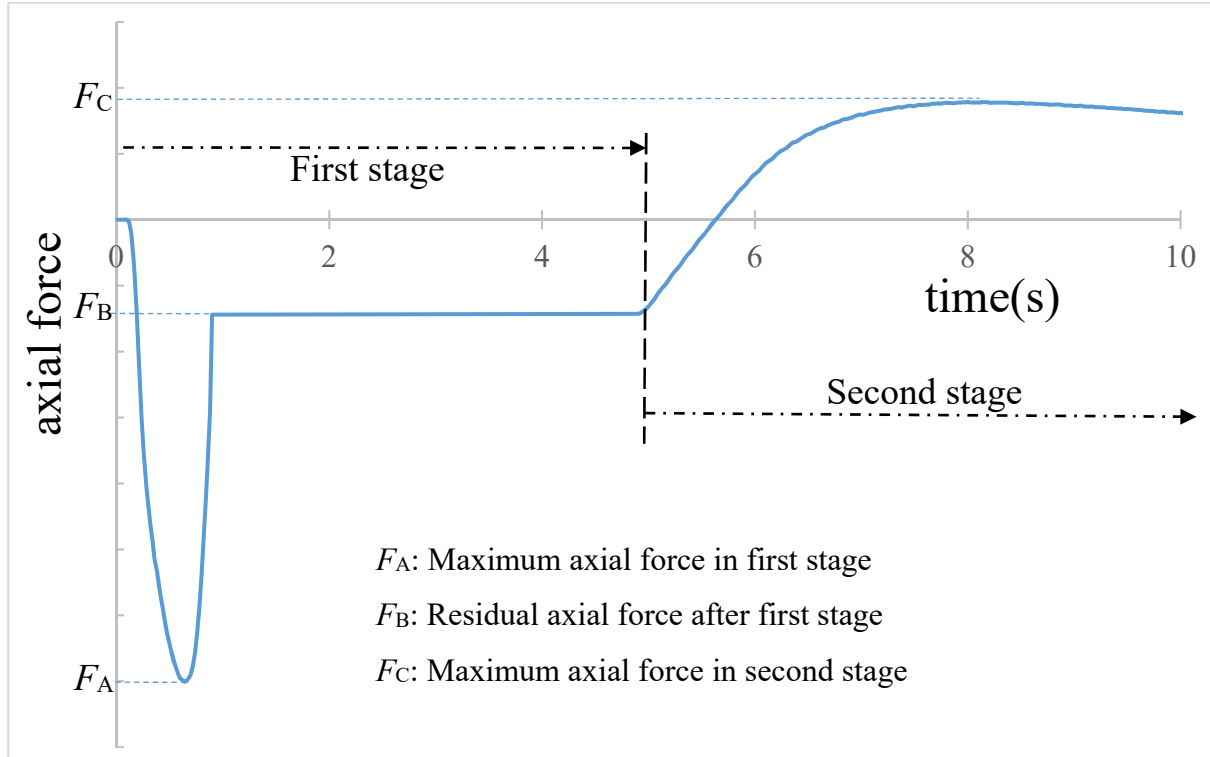


Fig. 2.6 Time history of axial force of the Basic case

2.2.5.2 Calculation of residual ultimate strength of tube under axial compression

At the second stage, the enforced displacement at the center of one tube end was imposed by a constant compressive velocity of 0.02m/s in the tube axial direction, meanwhile the other end was fixed in axial direction. The maximum value of axial force F_C shown in Fig. 2.6 will represent the bearing capacity of damaged tube. The difference value between F_C and F_B can be regarded as the residual ultimate strength of damaged tube, which was struck by lateral impact.

2.3 Effects of collision factors

In order to obtain a simplified formula for prediction of the residual ultimate strength of the damaged tube, a comprehensive parametric analysis is undertaken. The effects of various factors are studied, including the scantling parameter of the tube, the mass, velocity and size of the colliding body, and the collision location. Then the effect of different shapes of striking body is investigated, as well as a detailed analysis by considering various assemblies of mass and velocity at the same collision energy.

2.3.1 Parametric study of shape of tube and collision energy

The combinations of parameters selected in calculations are shown in Table 2.2. In all cases a rigid sphere with the diameter of 2.0m is modeled as the colliding object.

Table 2.2 Detail value of parameters in calculation cases

Case	L (m)	D (m)	t (m)	M (ton)	V_0 (m/s)
Basic	30	2.5	0.04	1000	5
L15	15	2.5	0.04	1000	5
L24	24	2.5	0.04	1000	5
L38	38	2.5	0.04	1000	5
L45	45	2.5	0.04	1000	5
D1.8	30	1.8	0.04	1000	5
D2.0	30	2.0	0.04	1000	5
D3.2	30	3.2	0.04	1000	5
D4.0	30	4.0	0.04	1000	5
T20	30	2.5	0.02	1000	5
T30	30	2.5	0.03	1000	5
T50	30	2.5	0.05	1000	5
T60	30	2.5	0.06	1000	5
M5	30	2.5	0.04	500	5
M8	30	2.5	0.04	800	5
M15	30	2.5	0.04	1500	5
M25	30	2.5	0.04	2500	5
V2	30	2.5	0.04	1000	2
V3	30	2.5	0.04	1000	3
V7	30	2.5	0.04	1000	7
V10	30	2.5	0.04	1000	10

cf.) L , D and t are the length, diameter and thickness of the tube member, respectively;

M is the mass of rigid impact sphere;

V_0 is the initial velocity of the rigid impact sphere before collision.

Colliding position is the center of middle span of the tube. Simply supported condition at both ends of tube is applied in all cases, just as the Basic case. By changing the scantling of the tubes

and the impact mass and velocity, a series of calculations is performed to investigate the parametric effect on the residual ultimate strength of damaged tubes.

2.3.2 Effect of offset in y direction (transverse location)

In the calculation of offset effect both in y direction and in z direction, not all the cases shown in Table 2.2 are calculated. Only these cases were calculated, Basic, L15, L45, D1.8, D4.0, T20, T60, M5, M25, V2 and V10.

Fig. 2.7 shows the definition of the offset of colliding position in y direction. By changing the impact angle α from 0° to 60° , the offset effect in y direction is investigated.

2.3.3 Effect of offset in z direction (longitudinal location)

In order to investigate the effect of colliding location in length on the residual deformation, four cases were performed and compared to each other. Fig. 2.8 shows the detail of colliding position for each calculation case. Where, the length of 3m is 10% of the tube length.

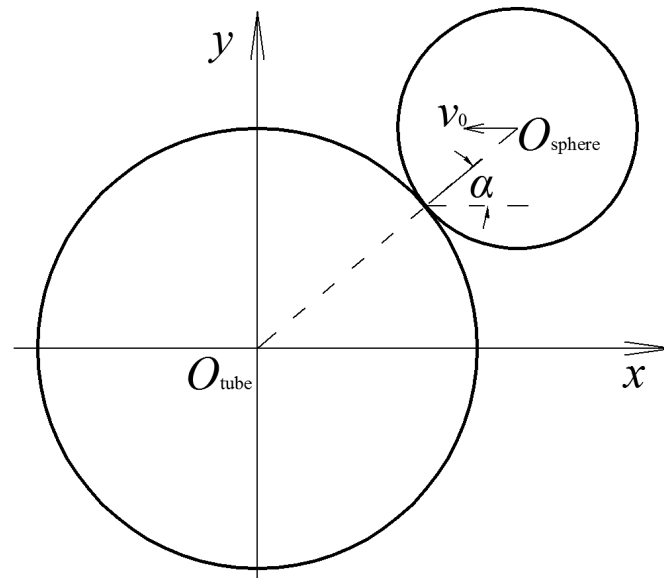


Fig. 2.7 Impact position offset in y direction

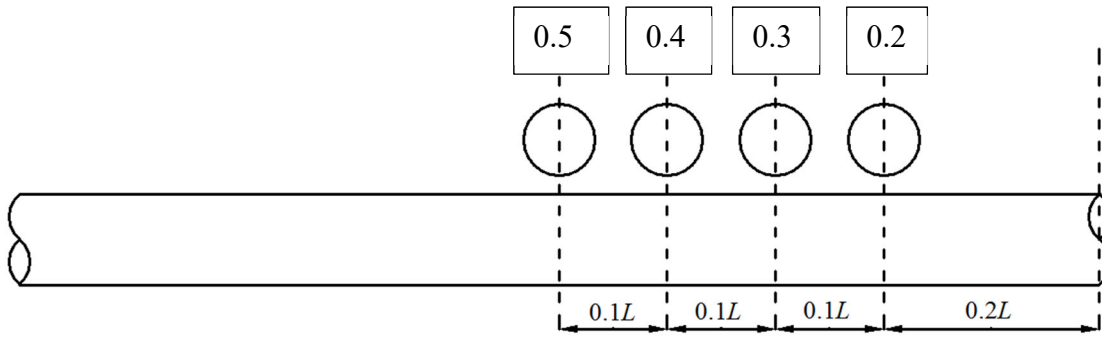


Fig. 2.8 Impact position offsets in z direction

2.3.4 Different assemblies of impact mass and velocity

Impact energy is given by the product of the impact mass and the square of velocity. In order to confirm that only the impact energy will influence on the residual ultimate strength of tube rather than the mass or velocity, five cases shown in Table 2.3 were calculated. And Case *1000-5 is the Basic case of this chapter. In all five cases, the tube scantling was the same as that in the Basic case. The change of impact mass was realized by changing the density of the impact rigid sphere.

Table 2.3 Different assemble of impact mass and velocity with same energy

Case	M (ton)	v_0 (m/s)
*25000-1	25000	1
*6250-2	6250	2
*1000-5 (Basic)	1000	5
*391-8	391	8
*250-10	250	10

2.3.5 Different sizes of colliding object

In order to examine the effect of different geometrical sizes of colliding objects, the calculations of colliding and residual ultimate strength were performed for three different radius (r), 0.3, 1.0 and 3.0m, of the rigid sphere body. Tubes' scantling was the same as the basic one. The lateral impact mass in all cases is 1000ton with the same initial impact velocity of 5m/s. In this section, $r=1.0$ m is the Basic case of this chapter. Fig. 2.9 shows the deformation of tube in collision, in which the tube and impact sphere was cut by plane in XOZ through the tube axis.

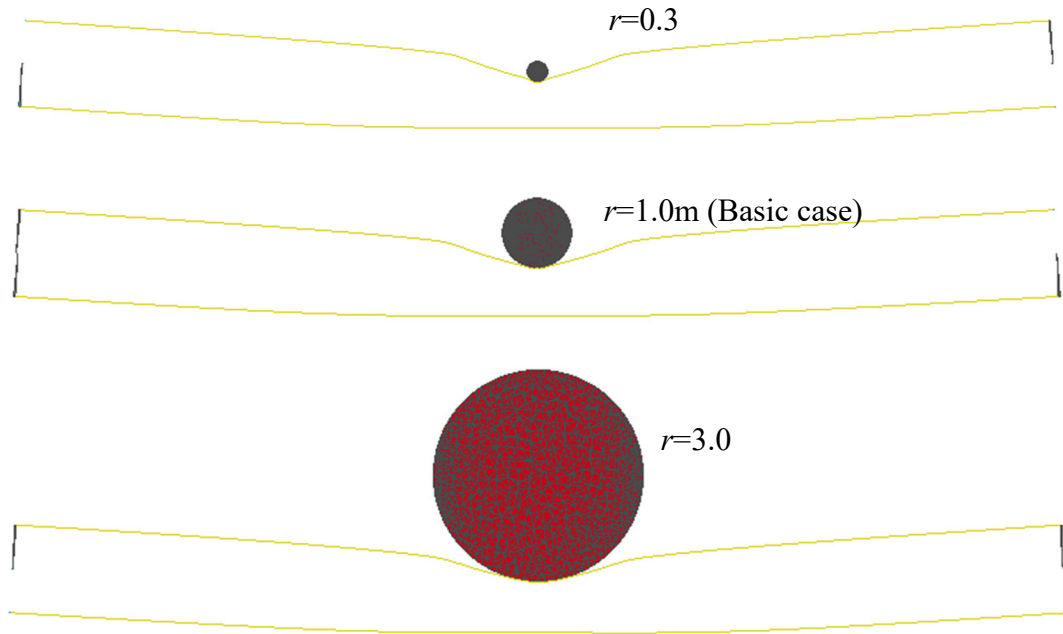


Fig. 2.9 Side view of collision situation of different sphere radius

2.4 Calculation results

In this chapter, the calculation results of the Basic case are shown in Section 2.4.1. Then, the calculation results of parametric study are shown in Section 2.4.2. Moreover, the results of effects of offset in y and z directions of impact position are shown in Section 2.4.3. Finally the results of effects of different assemblies of energy and different impact shapes are shown in Section 2.4.4 and Section 2.4.5.

2.4.1 Basic model

2.4.1.1 Residual deformation in collision

After collision, both the residual stress and the residual deformation exist. They are both the consequences of impact and appears to the structure in the same time as couples. However, the residual stress is complicated. It is difficult to show directly the relationship between residual ultimate strength and residual stress quantitatively. In the other hands, it is easy to show the relationship between residual ultimate strength and residual deformation, although not only the residual deformation but also the residual stress by collision is taking account in the calculation

of residual strength tube after collision. So the relationship between F_u/F_0 and δ_t/D is shown in Equation (1) in Section 2.4.2, the meaning of F_u and δ_t will be explained as well.

Fig. 2.10 shows the residual deformation of tube after collision for the Basic case. The displacement at front point consists of global displacement δ_g and local displacement δ_l . So, the local displacement is calculated from the total displacement by subtracting δ_g . As described in Fig. 2.5, time histories of both of global and local displacement at mid span for the Basic case are shown in Fig. 2.11. The magnitudes of local displacement and global displacement have same order in the Basic case, but this was not always true in other cases, which will be shown later in Section 2.4.2. And in all the calculation cases, the ultimate state for damaged tubes is the local collapse and local yielding in the struck area.

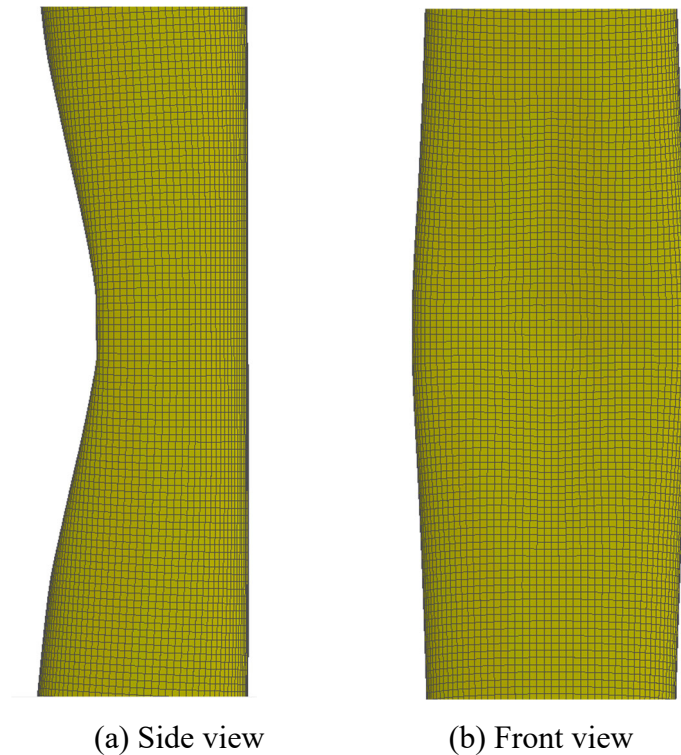


Fig. 2.10 Deformation at contact area of the Basic case

Two time moments, $t=0.64s$ and $t=4.5s$, are selected to show the distribution of axial stress (σ_z) in the vicinity of front point of the tube in Fig. 2.12. During the first stage, that is before 5s, the both ends of the tube is fixed in axial direction, then the tensile stress will be produced due to the global deflection of tube.

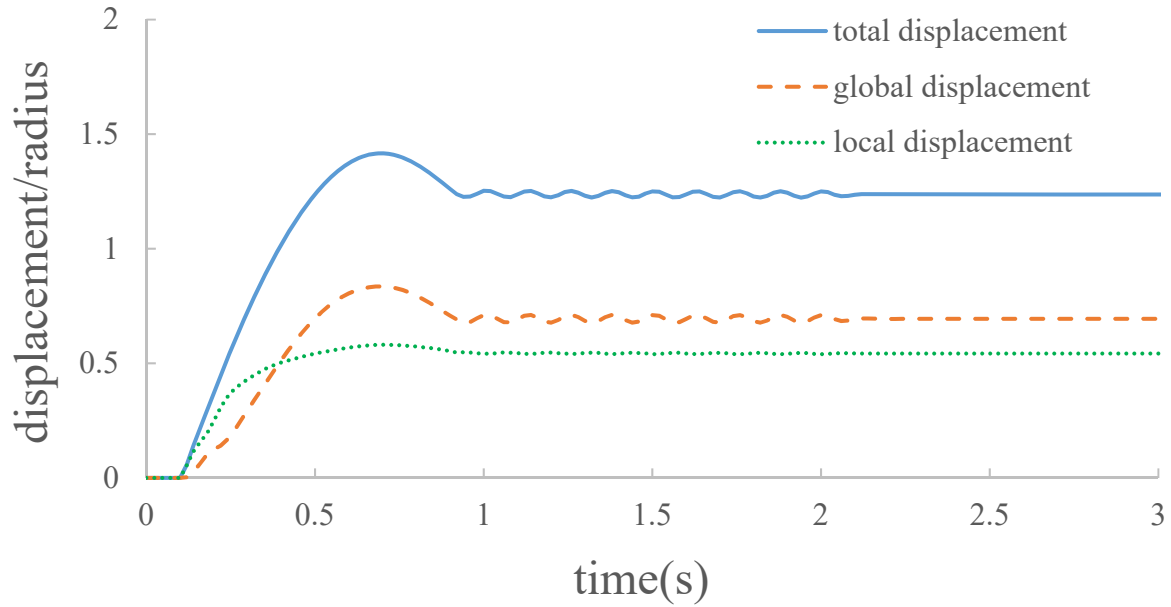


Fig. 2.11 Time history of contact area of the Basic case

At $t=0.64s$, due to the elastic global bending deflection of tube, the axial membrane stress at the contact side of tube is in compression. But in the vicinity of front point, the axial membrane stress is in tension due to the local deflection of contact area.

At $t=4.50s$, the stress distribution becomes different from that at $t=0.64s$. During the unloading stage of impact load, there is a tendency that the tube is trying to deform back to the original state. Since the spring back of local deformation in the vicinity of front point will be constrained by surround part of tube, the membrane stress at center part becomes in compression. But in global, the membrane stress of tube in axial direction is still in tension due to deflection of tube and constraint effect of axial displacement at both ends.

2.4.1.2 Residual ultimate strength of tube under axial compression

In Fig. 2.6 the axial force F_B is the residual axial force after lateral impact. It is produced by constraining the axial displacement at both ends. This axial force F_B is supported by the other members connecting to the both ends. The axial force F_C is the maximum axial force in second stage. Then, $F_u (= F_C - F_B)$ is the axial loading capacity of damaged pipe after lateral impact. This capacity is defined as the residual ultimate strength of damaged tube under axial compression.

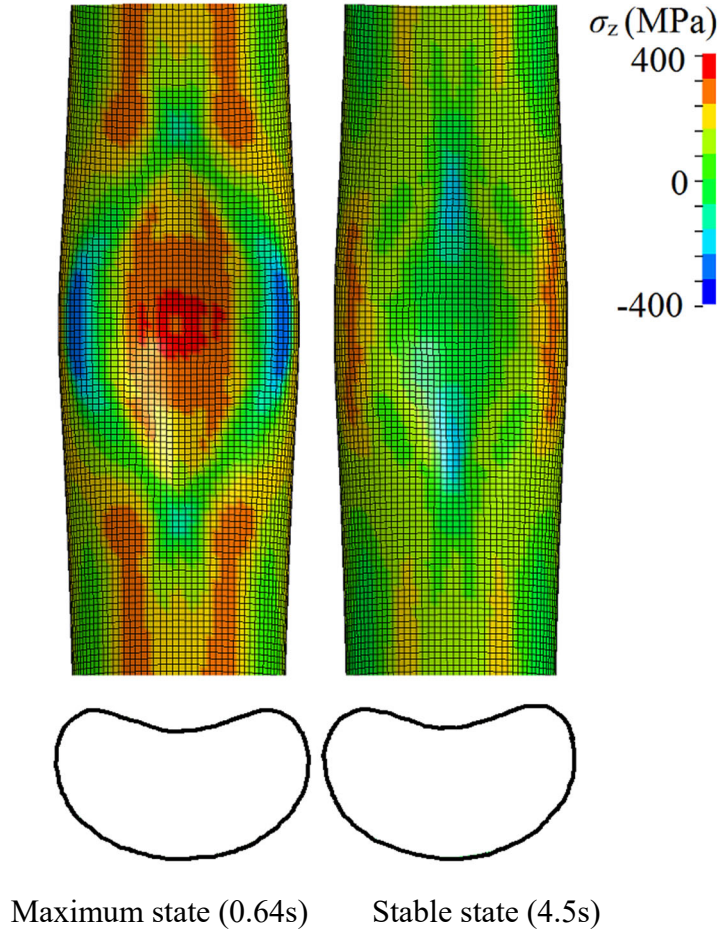


Fig. 2.12 Stress distribution in tube axial direction (σ_z) and cross section deformation of contact area of Basic case in the first stage

In order to remove the vibration of the tube after collision, a time depending damper was introduced into the calculation according the manual of LS-DYNA ^[42].

As shown in Fig. 2.6, this is the result of the Basic case, the damping function is available only from 2 to 4.9s. However in the second stage, the axial compressive velocity is 0.02m/s, which is a relatively low value. And there is no need to damp during the second stage.

2.4.2 Calculation results of parametric study

The calculation results of total deformation δ_t , global deformation δ_g and local deformation δ_l are shown in Table 2.4. The axial force F_B , F_C and F_u are also shown in Table 2.4.

Table 2.4 Calculation results of deformation, axial force and ultimate strength from parametric study

Case	V_t (m/s)	E_{ti} (MJ)	δ_t (m)	θ_y	δ_g (m)	δ_l (m)	δ_g/δ_t (%)	δ_l/δ_t (%)	F_B (MN)	F_C (MN)	F_u (MN)	F_0 (MN)	F_u/F_0 (%)
Basic	1.52	11.27	1.55	0.06	0.87	0.68	56	44	-14.34	17.74	32.08	73.83	43.44
L15	1.54	10.94	1.24	0.04	0.30	0.94	24	76	-23.67	22.10	45.78	73.83	62.00
L24	1.39	11.39	1.45	0.06	0.70	0.74	49	51	-13.27	20.19	33.46	73.83	45.32
L38	1.68	10.98	1.66	0.05	1.04	0.63	62	38	-14.65	15.30	29.95	73.83	40.57
L45	1.82	10.73	1.75	0.05	1.15	0.60	66	34	-14.91	14.17	29.08	73.83	39.39
D1.8	1.48	11.32	1.74	0.08	1.20	0.54	69	31	-8.27	8.01	16.28	53.16	30.62
D2.0	1.50	11.28	1.68	0.07	1.11	0.57	66	34	-10.34	10.28	20.62	59.06	34.91
D3.2	1.61	11.10	1.41	0.03	0.48	0.93	34	66	-19.52	33.22	52.74	94.50	55.81
D4.0	1.76	10.85	1.34	0.01	0.16	1.18	12	88	-34.46	57.80	92.26	118.12	78.10
T20	1.27	11.61	2.67	0.08	1.17	1.49	44	56	-1.38	3.08	4.45	36.91	12.07
T30	1.45	11.35	1.95	0.07	1.02	0.94	52	48	-7.71	8.88	16.59	55.37	29.96
T50	1.50	11.29	1.29	0.05	0.70	0.59	54	46	-19.16	29.16	48.32	92.28	52.36
T60	1.49	11.29	1.10	0.04	0.56	0.54	51	49	-24.05	43.55	67.60	110.74	61.04
M5	1.73	5.45	0.95	0.03	0.40	0.55	42	58	-15.42	28.75	44.17	73.83	59.82
M8	1.57	8.93	1.33	0.05	0.70	0.63	53	47	-14.31	20.76	35.06	73.83	47.49
M15	1.37	17.21	2.00	0.08	1.15	0.85	57	43	-11.55	12.96	24.50	73.83	33.19
M25	1.14	29.43	2.72	0.10	1.55	1.17	57	43	-5.71	8.00	13.71	73.83	18.57
V2	0.88	1.60	0.43	0.00	0.07	0.35	17	83	-15.78	56.48	72.26	73.83	97.88
V3	1.12	3.83	0.75	0.02	0.25	0.50	34	66	-17.50	36.48	53.98	73.83	73.12
V7	1.76	22.78	2.34	0.09	1.34	1.00	57	43	-8.59	10.18	18.77	73.83	25.42
V10	1.88	47.92	3.51	0.14	2.03	1.48	58	42	-1.49	4.68	6.17	73.83	8.36

cf.) V_t is the velocity of the rigid impact sphere after collision;

E_{ti} is the internal energy absorbed by the tube after collision, elastic and plastic strain energy;

δ_t is total deformation of the front point;

θ_y is boundary rotation of the front point;

δ_g is global deformation of the front point;

δ_l is local deformation;

(the above six results are obtained at the stable state in the first stage, $t=4.5s$)

F_B is axial force of point B, the stable axial force after collision in the first stage;

F_C is axial force of point C, the maximum axial force in the second stage;

F_u is ultimate strength of damaged tube under axial compression, equals F_C minutes F_B ;

$F_0 = \sigma_y \times (\pi D t)$ is ultimate strength of intact tube under axial compression of cases in this chapter.

From Table 2.4, when the tube length is larger or tube diameter is smaller, the global displacement becomes larger and local displacement becomes smaller, and the dominant component switched from local to global displacement. In thicker tube, both global and local displacement becomes smaller. Meanwhile, when the impact energy increased, both the global and local displacement increased, and the dominant component switched from local to global displacement.

It is clear that if the tube's length is smaller, diameter is larger and shell is thicker, the tube has higher capacity to tolerate lateral impact. And if the impact energy is smaller, that means the deformation of the tube is relatively slighter, the residual ultimate strength of the damaged tube is higher. So, it is desirable to derive one parameter which could estimate the ability for axial loading of the damaged tube, by using the ratio of the impact energy to the capacity of tube which is related to tube's length, diameter, and thickness. It will be described later in Section 2.5.

According to the calculation results in Table 2.4. The relationships between F_u/F_0 and δ_l/D or δ_g/D are not clear (δ_l is local deformation and δ_g is global deformation). So the relationship between the residual ultimate strength and the total deformation of the tube is shown in Fig. 2.13. In the figure, non-dimensional parameters are applied, F_u/F_0 and δ_t/D . All the results obey the same tendency. And a simulated equation is proposed as following,

$$\frac{F_u}{F_0} = f\left(\frac{\delta_t}{D}\right) = e^{-1.5\left(\frac{\delta_t}{D}\right)^{1.25}} \quad (2.1)$$

Where, F_0 is the ultimate strength of intact tube, δ_t is total deformation.

It is confirmed that the ultimate strength of the tube with dimensions satisfying the API rule becomes almost its yield strength. Therefore, $F_0 = \sigma_y \times (\pi D t)$ is applied in this study.

And the standard deviation of Equation (2.1) is 0.050 which is calculated by

$$\sigma = \sqrt{\frac{1}{N} \sum_1^N \left[\left(\frac{F_u}{F_0} \right)_i - f \left(\frac{\delta_t}{D} \right)_i \right]^2} \quad (2.2)$$

This value is small enough. It means that the residual ultimate strength of damaged tube by collision can be estimated accurately with the proposed formula.

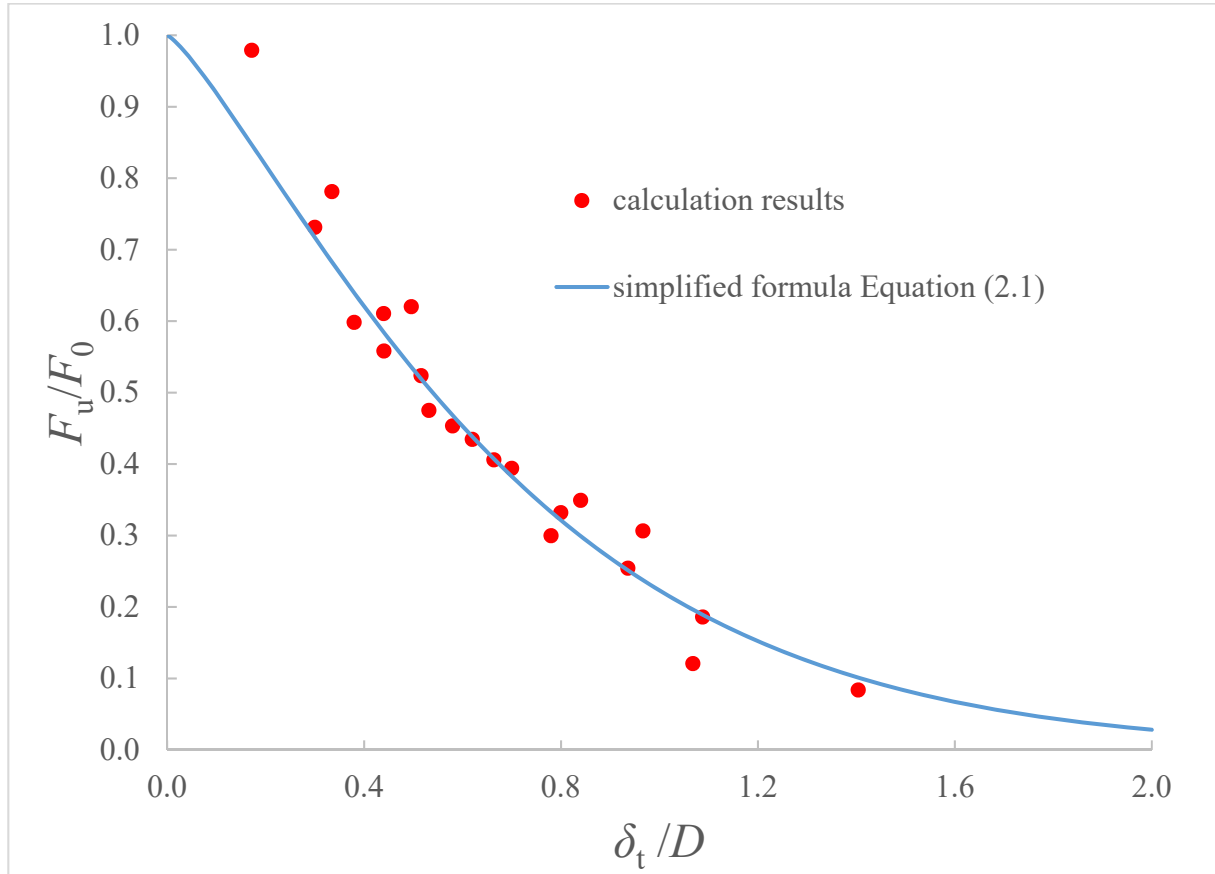


Fig. 2.13 Relationship between the ratio of ultimate strength of damaged tube to that of intact one and the ratio of total deformation to tube diameter

2.4.3 The effect of location of impact

2.4.3.1 Offset effect in y direction (transverse location)

In Table 2.5, the impart angle of 0° means that the colliding mass impacts just on the axis at the mid span of the tube. The others cases, that α equals to 15° , 30° , 45° , and 60° , represent the cases that the colliding mass attack to the tube with eccentricity of α degree which was defined in Fig. 2.7.

Table 2.5 Calculation results of absorbed energy and ultimate strength considering offset effect in y direction

Impact angle α	0°		15°		30°		45°		60°	
Case	E_{ti} (MJ)	F_u (MN)	E_{ti} (MJ)	F_u (MN)	E_{ti} (MJ)	F_u (MN)	E_{ti} (MJ)	F_u (MN)	E_{ti} (MJ)	F_u (MN)
Basic	11.27	32.07	11.24	30.85	10.17	27.45	4.44	50.20	1.17	69.96
L15	10.94	45.78	10.87	45.94	9.82	46.75	4.95	53.90	1.54	66.06
L45	10.73	29.08	10.72	26.98	9.95	25.24	3.30	47.25	0.74	69.07
D1.8	11.32	16.28	11.26	15.35	10.45	16.72	5.15	16.79	0.73	53.03
D4.0	10.85	92.26	10.76	92.71	9.35	96.07	5.07	98.71	1.59	106.18
T20	11.61	4.45	11.55	4.03	11.03	3.35	2.25	13.29	0.35	28.88
T60	11.29	67.60	11.16	68.56	9.77	69.94	5.59	101.76	3.60	103.56
M5	5.45	44.17	5.39	44.61	4.59	47.64	2.44	66.14	0.82	72.64
M25	29.43	13.71	29.29	12.56	28.50	12.51	8.85	25.35	1.38	67.46
V2	1.60	72.26	1.56	72.65	1.24	73.27	0.82	74.44	0.36	79.49
V10	47.92	6.17	47.75	8.86	46.06	11.57	9.38	20.37	1.56	67.41

cf.) E_{ti} : the internal energy absorbed by the tube after collision;

F_u : ($=F_C - F_B$), the ultimate strength of damaged tube under axial compression.

Among these cases, the case which indicate the smallest residual ultimate strength is not unique. In general, the case of the impact angle of 0° shows the smallest residual ultimate strength. Because the side way movement of colliding mass will take place after impact when collided with eccentricity. Then, the impact will be mitigated.

But, when the length of tube is large, the diameter of tube is small, or the thickness is small, the case of the impact angle of 15° or 30° shows the smallest residual ultimate strength. And also, when the mass of impact is large, the case of the impact angle of 30° shows the smallest residual ultimate strength. In these tubes, the severe damage had happened and the residual ultimate strength after impact was small. The reason that the impact angle α of 15° or 30° gives the smaller residual ultimate strength than 0°, when the severe damage had happened by collision, can be explained as follows.

When the colliding mass impacts just on the axis of the tube, the deformation of the tube is only the bending. For 30° impact, the equivalent impact velocity decreases due to the angle, but not too much. In this case, the tube suffers not only bending but also torsion. So the couple effect will lead to the reduction of the ultimate strength compared to that of 0° impact. As shown in Fig. 2.14, this tendency is clearer when the large deformation takes place in collision.

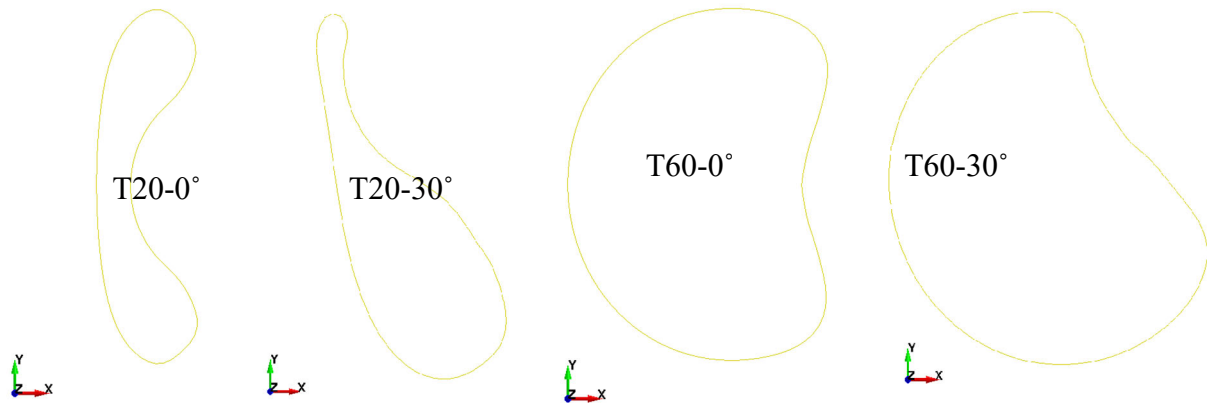


Fig. 2.14 Deformed cross section of impact part of the tube of Case T20 T60 and Case T20- 30° T60- 30°

2.4.3.2 Offset effect in in z direction (longitudinal location)

The calculation results are shown in Table 2.6. From the results, when the impact location approach to the middle span of the tube from the end, the tube absorbed energy is almost in the same level while the residual ultimate strength of damaged tubes decreases. The reason is that the ultimate strength of simply supported beam is weaker in the case of loading at middle span than in case of loading at near ends.

The effect of offset in z direction has no influence on the deformation mode. And the deformed cross sections are similar to each other as shown in Fig. 2.15.

When the same amplitude of damage takes place, the tube with damage at mid of span will show the smallest residual ultimate strength.

Table 2.6 Calculation results of absorbed energy and ultimate strength considering offset effect in z direction

Impact position	0.2		0.3		0.4		0.5	
Case	E_{ti} (MJ)	F_u (MN)	E_{ti} (MJ)	F_u (MN)	E_{ti} (MJ)	F_u (MN)	E_{ti} (MJ)	F_u (MN)
Basic	11.44	38.69	11.33	33.67	11.28	32.45	11.27	32.07
L15	11.34	57.10	11.11	50.86	10.98	48.00	10.94	45.78
L45	11.02	32.97	10.86	30.77	10.76	29.41	10.73	29.08
D1.8	11.47	18.96	11.36	17.21	11.32	16.52	11.32	16.28
D4.0	11.42	102.60	11.06	99.40	10.90	94.33	10.85	92.26
T20	11.70	8.22	11.64	5.65	11.61	4.71	11.61	4.45
T60	11.38	84.68	11.32	73.88	11.30	69.00	11.29	67.60
M5	5.52	55.39	5.47	48.12	5.45	44.98	5.45	44.17
M25	29.63	18.86	29.50	15.20	29.45	14.00	29.43	13.71
V2	1.68	74.35	1.63	73.71	1.61	72.62	1.60	72.26
V10	48.13	9.41	47.99	8.97	47.94	7.85	47.92	6.17

cf.) E_{ti} : the internal energy absorbed by the tube after collision;

F_u : ($=F_C - F_B$), the ultimate strength of damaged tube under axial compression.

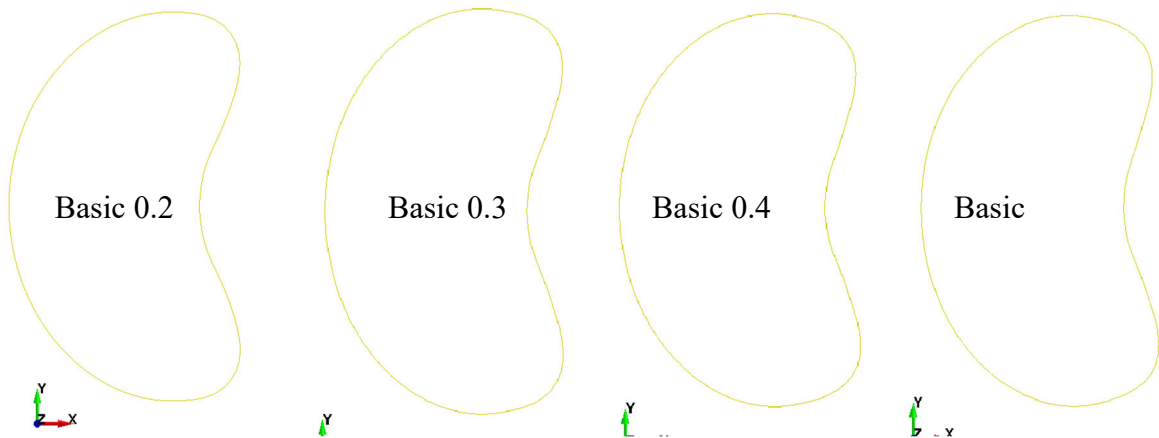


Fig. 2.15 Deformed cross section of impact part of the tube of Case Basic 0.2, 0.3, 0.4 and Basic case.

2.4.4 The effect of different assemblies of impact mass and velocity

Table 2.7 shows the calculation results of cases explained in Section 2.3.3.4. It is found that the same impact energy will lead to almost same residual ultimate strength. Different assemblies of

mass and velocity had merely slightly influenced on the calculation results of the residual ultimate strength of damaged tubes.

Table 2.7 Calculation results comparison with different impact mass and velocity

Case	M (ton)	V_0 (m/s)	V_t (m/s)	E_{ti} (MJ)	F_B (MN)	F_C (MN)	F_u (MN)
*25000-1	25000	-1	0.296	11.36	-14.41	16.76	31.17
*6250-2	6250	-2	0.601	11.29	-14.36	17.21	31.57
*1000-5 (Basic)	1000	-5	1.518	11.26	-14.34	17.74	32.08
*391-8	391	-8	2.421	11.26	-13.20	17.50	30.70
*250-10	250	-10	3.012	11.29	-12.47	17.26	29.73

cf.) E_{ti} : the internal energy absorbed by the tube after collision;

F_u : ($=F_C - F_B$), the ultimate strength of damaged tube under axial compression.

2.4.5 The effect of size of colliding part

Table 2.8 shows the calculation results of cases illustrated in Section 2.3.3.5. It is shown that the radius of the rigid impact sphere had little influence on the ultimate strength of the damaged tube. However, due to the same initial energy of the impact body and the same internal energy absorbed by the tube, there is little difference of the ultimate strength between the different sizes of colliding mass.

Table 2.8 Calculation results comparison with different shape of impact spheres

Case	V_t (m/s)	E_{ti} (MJ)	F_B (MN)	F_C (MN)	F_u (MN)
$r=0.3\text{m}$	1.490	11.29	-14.77	18.22	32.99
$r=1.0\text{m}$ (Basic)	1.518	11.26	-14.34	17.74	32.08
$r=3.0\text{m}$	1.517	11.26	-13.65	16.97	30.62

cf.) E_{ti} : the internal energy absorbed by the tube after collision;

F_u : ($=F_C - F_B$), the ultimate strength of damaged tube under axial compression.

2.5 Simplified formula

According to the results in Table 2.4 in Section 2.4.2, the effect of tube shape and impact energy could be summarized. Then the following formula is proposed to simulate the residual ultimate strength of damaged tubes:

$$\frac{F_u}{F_0} = e^{-0.7\lambda} \quad (2.3)$$

$$\text{Where, } \lambda = \frac{0.5Mv_0^2}{7.575\sigma_y L^{-0.55} D^2 t^{1.55}} ;$$

the unit of L , D and t is m, unit of M is kg, unit of v_0 is m/s, and unit of σ_y is Pa;

F_u is the residual ultimate strength of damaged tube;

F_0 is the ultimate strength of intact tube.

In the above equation, λ is a non-dimensional parameter. The molecule of the equation of λ is the impact energy, and the denominator of it is regarded as the absolute anti impact capacity of the tube suffers the lateral impact. So λ could be treated as the relatively anti impact parameter of the certain impact situation.

Although Equation (2.1) and Equation (2.3) both can be referred to estimate the residual ultimate strength of a damaged tube after collision with acceptable accuracy. The difference is as following. Equation (2.1) is a description of two output data from a collision case. That means, only after a collision actually take place, the residual ultimate strength of damaged tube could be estimated. Equation (2.1) produced by curve fitting of date. But, it also shows the total deformation (neither of local nor global deformation) gives dominant effect on residual strength as stated before. Therefore, if it is needed to judge the acceptable damage of the tube from the residual deformation after collision, Equation (2.1) is a good choice.

Contrastively, from the definition of λ in Equation (2.3), all the parameters are the input data of a collision case. It shows that not only the dimension of tube but also kinematic energy of colliding ship has the dominant effects on the residual strength of tube. As a result, it is possible to estimate the residual ultimate strength of a tube before a potential collision actually takes place. In the other hand, according to the above study, the acceptable value of λ is obtained. The acceptable mass and velocity of a vessel that approach the tube of a jacket platform can be evaluated.

The calculation results of ultimate strength of damaged tubes shown in Section 2.4.3.2 are plotted in Fig. 2.16. The ultimate strength of damaged tubes is normalized by the ultimate strength of each intact tube, F_0 . Equation (2.3) is also shown by the solid line.

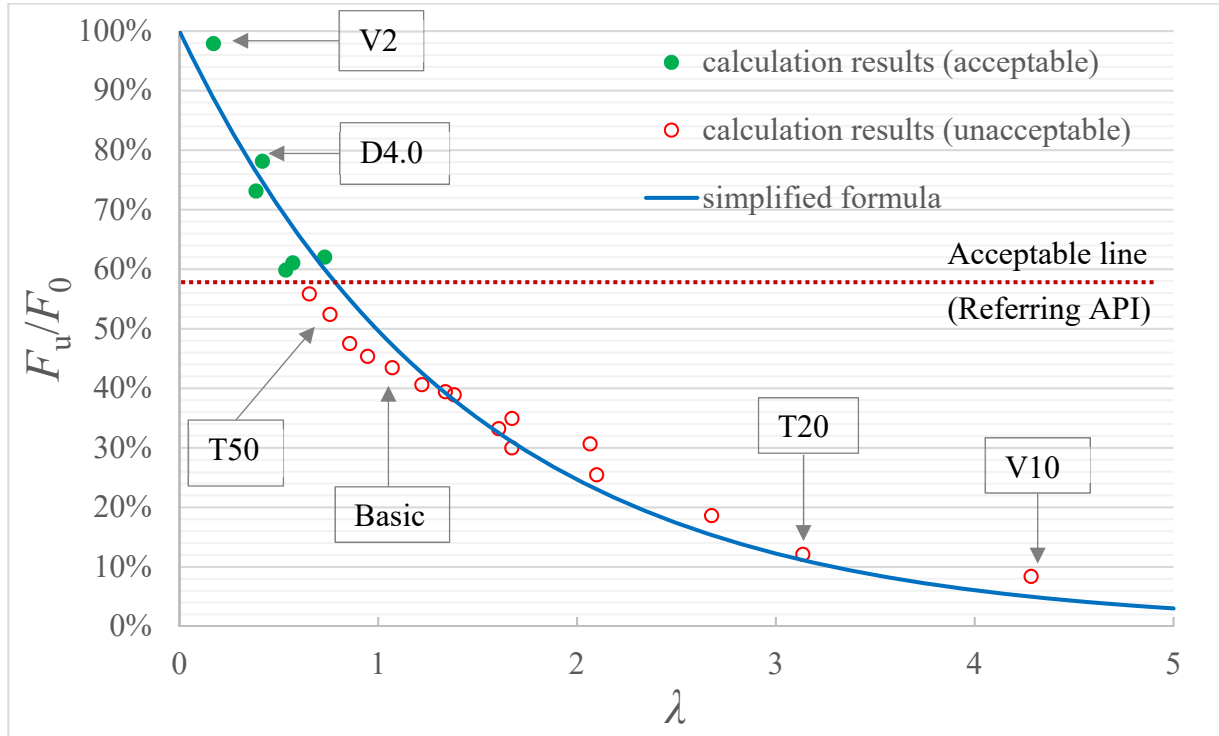


Fig. 2.16 Relationship between calculated residual ultimate strength and proposed parameter λ

FE calculation results are plotted with solid and open circles. The difference of solid and open circles will be explained later. It is confirmed that the proposed formula can predict accurately the reduction of ultimate strength of tube due to collision. As for the residual ultimate strength estimated using Equation (2.3), the standard deviation of numerical results is 0.049.

As shown in Section 2.4.4, the different assemblies mass and velocity will lead to same residual ultimate strength. As also shown in Section 2.4.5, there is little difference of the ultimate strength between the different sizes of colliding mass when the impact energy is the same. As shown in Section 2.4.4, the residual ultimate strength of damaged tubes decreases when the impact location approach to the middle span of the tube from the end. Then for the above cases, the residual ultimate strength of tube after collision damaged can be predict by utilizing Fig. 2.16 and Equation (2.3). It must be declared that the collision situation described by Equation

(2.3) is between the tube members and the bulbous bow structure which might be the limitation of application of Equation (2.3).

In the case of offset impact in y direction (transverse location) shown in Section 2.4.3.1, 0° impact situation is not always the severe situation. However, it is important to clearly propose the judgment criterion. As shown in Fig. 2.16, all the calculation results can be divided into two groups. One is the acceptable, which is above the line. The other the unacceptable, which is below the line. For the cases belongs the acceptable group, 0° impact is the most severe situation. From the safety side consideration, 0° impact case is investigated. For the cases belongs to unacceptable group, 0° impact is already unacceptable. So it is not of much significance to investigate which degree is the most severe situation. And the judging criterion does not change.

Based on the API rules ^[13], the allowable design axial capacity was calculated. And the calculation results for the residual ultimate strength after collision σ_u is compared with the allowable design axial capacity σ_a by API rules ^[13]. (The calculation procedure and results based on the API rules ^[13] will be explained in Appendix.) When the σ_u is larger than σ_a , the solid circle is used, and when σ_u is smaller than σ_a , the open circle is used in Fig. 2.16.

Seeing Fig. 2.16, a horizontal line could be draw to separate the acceptable points and unacceptable points with the F_u/F_0 value of 58%, approximately. Then, a critical ratio of residual ultimate strength of damaged tube to that of intact one, F_u/F_0 of 0.58, is suggested. Then, the criteria value of λ of 0.78 is proposed. It is advised that, when the value of λ falls down to 0.78, the damaged tube must be repaired or replaced.

2.6 Applicability of proposed formula

In order to clarify the variation of the tube scantlings and material properties due to manufacturing error, the effect of variations of tube scantlings and material properties is investigated in this section. In the non-dimensional simplified formula Equation (2.3), six parameters are selected to make up the estimation criteria λ . In real cases, each parameter has its own variation range, impact mass velocity, tube length, diameter, thickness and material yield stress. The effect of variation of impact energy will be studied later in Chapter 5.

Considering the manufacturing procedure of steel tube and large scantling of tube, the percentage of variation of L and D is very limited. So the tube shell thickness is the major parameter out of tube scantlings.

Beside of shell thickness, two more parameters are selected for investigating the effect of variance of these. One more value of material Young's modulus is selected. Three more values of yield stress of material are selected. Moreover the effects of the variation of these three parameters are investigated in Section 2.6.1, 2.6.2 and 2.6.3, respectively.

2.6.1 The effect of variation of tube shell thickness

The parameter of t is investigated in this section. Considering about the Basic case,

$$L=30\text{m}, \quad D=2.5\text{m}, \quad t=40\text{mm}, \quad \sigma_y=235\text{MPa}, \quad E=2.1 \times 10^5 \text{MPa}.$$

As shown above, the value of thickness obeys the normal distribution, and the ratio of standard derivation to mean value, σ/μ is 0.05 according to Gaspar et al ^[34] (μ is the mean value and σ is the stander derivation). And considering the mean value of the tube should be larger than the design value, to avoid the situation that the actual tube shell thickness is much less than the design value. So the additional values of thickness is selected to be 42mm and 44mm. The possibility is as follows, and the residual ultimate strength of damaged tube of both thicknesses are compared to that of Basic case.

$$\Phi(t \geq 40, \mu=40, \sigma=2)=50\%;$$

$$\Phi(t \geq 40, \mu=42, \sigma=2.1)=83\%;$$

$$\Phi(t \geq 40, \mu=44, \sigma=2.2)=96.5\%.$$

The residual ultimate strength calculation result is shown in Table 2.9. The variation of t has little influence on the accuracy of Equation (2.3). The reason is that, in the derivation of Equation (2.3), the variable parameter of t is from 20~60mm. And all the calculation results obey the tendency of Equation (2.3). So the variation of t will also obey the same tendency. The same situation occurs when changing the values of L or D .

Table 2.9 Comparison of calculation results of different values of shell thickness

Case	Simulated F_w/F_0	Calculated F_w/F_0	Error (%)
$t=40\text{mm}$ (Basic)	0.4345	0.4725	8.74
$t_1=42\text{mm}$	0.4510	0.4990	10.64
$t_2=44\text{mm}$	0.4683	0.5237	11.84

cf.) Error = (Simulated - Calculated) / Calculated $\times 100\%$

2.6.2 The effect of variation of tube material Young's modulus

The parameter of Young's modulus E is investigated in this section, another value of Young's modulus is selected according to Gaspar et al ^[34],

$$E_1=2.3 \times 10^5 \text{MPa}.$$

The other parameters are the same as the Basic case. The residual ultimate strength calculation result is shown in Table 2.10. According to the comparison results, the influence of Young's modulus is very limited that could be neglected.

Table 2.10 Comparison of calculation results of different values of Young's modulus

Case	Simulated F_w/F_0	Calculated F_w/F_0	Error (%)
$E=2.1 \times 10^5 \text{MPa}$ (Basic)	0.4345	0.4725	8.74
$E_1=2.3 \times 10^5 \text{MPa}$	0.4725	0.4409	7.17

cf.) Error = (Simulated - Calculated) / Calculated $\times 100\%$

2.6.3 The effect of variation of tube yield stress of material

In the above calculations, the value of yield stress is selected to be 235MPa, since the mild steel is selected. However, the value of yield stress is not constant. So in order to clarify the effect of yield stress, six out of all the cases in Table 2.2 are selected. Two cases are above the acceptable line: V2 and D40. Two cases are just below the acceptable line: T50 and Basic. Two cases are far below the acceptable line: T20 and V10.

$\sigma_y=235\text{MPa}$ is the fifth percentile value, the man value and standard deviation is shown as follows according to Gaspar et al ^[34], $\mu=269$; $\sigma=0.08\times 269=21.52$. (μ is the mean value and σ is the standard derivation)

$$\Phi(\sigma_y \geq 269) = 1 - \Phi(269) = 50.01\%;$$

$$\Phi(\sigma_y \geq 255) = 1 - \Phi(255) = 74.84\%;$$

$$\Phi(\sigma_y \geq 235) = 1 - \Phi(235) = 95.47\%.$$

So three additional values of yield stress is chosen, $\sigma_{y1}=255\text{MPa}$, $\sigma_{y2}=269\text{MPa}$ and $\sigma_{y3}=300\text{MPa}$. The comparison result between the simulated formula and the calculation results with different values of yield stress is shown in Fig. 2.17, and Table 2.11 to Table 2.16. As shown in results, the simplified formula Equation (2.3) is also valid while different value of yield stress of material is applied.

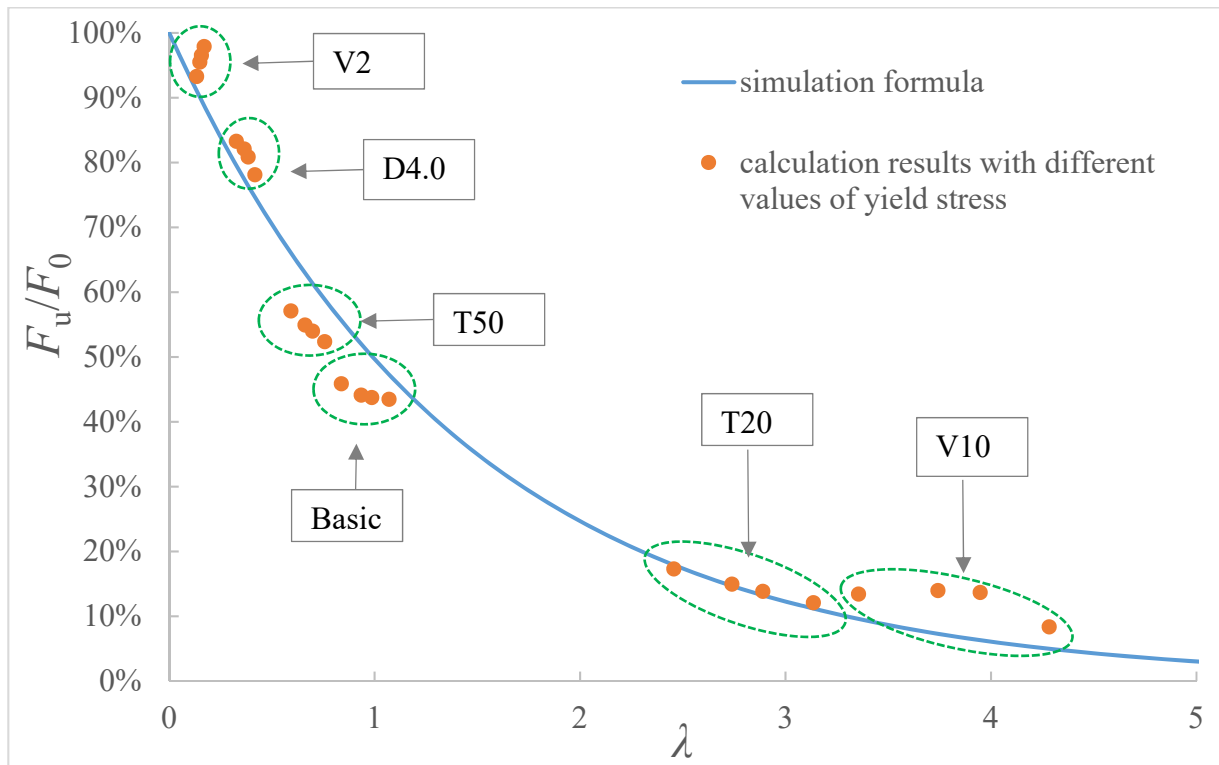


Fig. 2.17 Comparison results between simulated formula and calculation results with different values of yield stress

Table 2.11 Comparison of calculation results of different values of yield stress (Basic)

Case	Simulated F_u/F_0	Calculated F_u/F_0	Error (%)
$\sigma_y=235\text{MPa}$ (Basic)	0.4345	0.4725	8.74
$\sigma_{y1}=255\text{MPa}$	0.5011	0.4374	14.57
$\sigma_{y2}=269\text{MPa}$	0.5195	0.4411	17.76
$\sigma_{y3}=300\text{MPa}$	0.5558	0.4585	21.24

cf.) Error = (Simulated - Calculated) / Calculated $\times 100\%$

Table 2.12 Comparison of calculation results of different values of yield stress (V2)

Case	Simulated F_u/F_0	Calculated F_u/F_0	Error (%)
$\sigma_y=2235\text{MPa}$ (V2)	0.8870	0.9788	-9.38
$\sigma_{y1}=255\text{MPa}$	0.8953	0.9654	-7.25
$\sigma_{y2}=269\text{MPa}$	0.9005	0.9550	-5.71
$\sigma_{y3}=300\text{MPa}$	0.9103	0.9326	-2.39

cf.) Error = (Simulated - Calculated) / Calculated $\times 100\%$

Table 2.13 Comparison of calculation results of different values of yield stress (D40)

Case	Simulated F_u/F_0	Calculated F_u/F_0	Error (%)
$\sigma_y=235\text{MPa}$ (D40)	0.7461	0.7810	-4.47
$\sigma_{y1}=255\text{MPa}$	0.7635	0.8085	-5.57
$\sigma_{y2}=269\text{MPa}$	0.7743	0.8208	-5.67
$\sigma_{y3}=300\text{MPa}$	0.7950	0.8327	-4.53

cf.) Error = (Simulated - Calculated) / Calculated $\times 100\%$

Table 2.14 Comparison of calculation results of different values of yield stress (T50)

Case	Simulated F_u/F_0	Calculated F_u/F_0	Error (%)
$\sigma_y=235\text{MPa}$ (T50)	0.5883	0.5236	12.35
$\sigma_{y1}=255\text{MPa}$	0.6133	0.5397	13.64
$\sigma_{y2}=269\text{MPa}$	0.6291	0.5492	14.54
$\sigma_{y3}=300\text{MPa}$	0.6600	0.5709	15.59

cf.) Error = (Simulated - Calculated) / Calculated $\times 100\%$

Table 2.15 Comparison of calculation results of different values of yield stress (T20)

Case	Simulated F_u/F_0	Calculated F_u/F_0	Error (%)
$\sigma_y=235\text{MPa}$ (T20)	0.1113	0.1207	-7.75
$\sigma_{y1}=255\text{MPa}$	0.1322	0.1384	-4.46
$\sigma_{y2}=269\text{MPa}$	0.1469	0.1493	-1.59
$\sigma_{y3}=300\text{MPa}$	0.1791	0.1728	3.66

cf.) Error = (Simulated - Calculated) / Calculated $\times 100\%$

Table 2.16 Comparison of calculation results of different values of yield stress (V10)

Case	Simulated F_u/F_0	Calculated F_u/F_0	Error (%)
$\sigma_y=235\text{MPa}$ (V10)	0.0498	0.0836	-40.36
$\sigma_{y1}=255\text{MPa}$	0.0631	0.1364	-53.78
$\sigma_{y2}=269\text{MPa}$	0.0728	0.1394	-47.78
$\sigma_{y3}=300\text{MPa}$	0.0955	0.1340	-28.77

cf.) Error = (Simulated - Calculated) / Calculated $\times 100\%$

Another meaning of this comparison result is that, applying materials with higher yield stress (up to 300MPa) will hardly help to improve the residual ultimate strength. Although, the absolute value of average residual compressive stress bearing capacity is improved, the ratio of ultimate strength of damaged tube to that of intact one will not change a lot.

2.7 Conclusions

By the application of nonlinear numerical calculation, the residual ultimate strength of collided tubes was investigated. The collision situation is assumed between the tube member and supply vessel bulbous bow. The simply supported tubes collided by a rigid sphere body in the middle span of the tube length were calculated, by changing the tube length, diameter and thickness and impact mass and velocity. The L/D range of tubes is from 6 to 18 and the D/t range is from 41.6 to 125. The ratio of the ultimate strength of damaged tube to intact one was obtained by numerical calculations. And a simplified formula for predicting the residual ultimate strength of damaged tube by collision impact are derived by using the parameter of λ , which could be calculated by using the length, diameter, and thickness of tube as well as impact energy.

The applicability of the simplified formula was also checked by changing the colliding conditions, such as for different assemblies mass and velocity, different sizes of colliding mass, and different impact location in length and breadth. Good agreement of results from simplified formula and numerical calculation could be achieved as well.

Then, by comparing with the allowable compressive stress proposed in API rules ^[13], for a critical ratio of residual ultimate strength of damaged tube to that of intact one F_w/F_0 , the reduction ration of 0.58 is suggested. Then, the criteria value for λ is proposed to be 0.78. It is advised that, when the value of λ falls down to 0.78, the damaged tube must be repaired or replaced.

Finally, the effect of variation of tube scantlings and material physical properties due to manufacturing error is investigated. Based on the calculation results, that effect has almost no influence on the accuracy of proposed simplified formula, especially the yield stress of material. While changing the parameter values, the results of residual ultimate strength from numerical calculation also obey the tendency described by the simplified formula.

2.8 Appendix: comparison to API rules

According to the API rules ^[13] shown in Chapter 1, the allowable axial compressive stress, σ_a , estimated by the above content are shown in Table 2.17. By comparing the value of σ_u and σ_a , the larger one is marked by underscores shown in Table 2.17.

Table 2.17 Comparison of residual ultimate strength between calculation results and allowable axial compressive stress of API rules ^[13]

Case	L (m)	D (m)	t (m)	Calculation result: F_u (MN)	Calculation result: σ_u (MPa)	API required: σ_a (MPa)
Basic	30	2.5	0.04	32.08	102.17	<u>129.18</u>
L15	15	2.5	0.04	45.78	<u>145.80</u>	135.98
L24	24	2.5	0.04	33.46	106.56	<u>132.10</u>
L38	38	2.5	0.04	29.95	95.38	<u>124.91</u>
L45	45	2.5	0.04	29.08	92.61	<u>120.83</u>
D1.8	30	1.8	0.04	16.28	72.01	<u>122.73</u>
D2.0	30	2.0	0.04	20.62	82.09	<u>125.12</u>
D3.2	30	3.2	0.04	52.74	131.22	<u>132.59</u>
D4.0	30	4.0	0.04	92.26	<u>183.64</u>	134.77
T20	30	2.5	0.02	4.45	28.34	<u>130.14</u>
T30	30	2.5	0.03	16.59	70.45	<u>129.56</u>
T50	30	2.5	0.05	48.32	123.11	<u>129.13</u>
T60	30	2.5	0.06	67.6	<u>143.52</u>	129.13
M5	30	2.5	0.04	44.17	<u>140.67</u>	129.18
M8	30	2.5	0.04	35.06	111.66	<u>129.18</u>
M15	30	2.5	0.04	24.5	78.03	<u>129.18</u>
M25	30	2.5	0.04	13.71	43.66	<u>129.18</u>
V2	30	2.5	0.04	72.26	<u>230.13</u>	129.18
V3	30	2.5	0.04	53.98	<u>171.91</u>	129.18
V7	30	2.5	0.04	18.77	59.78	<u>129.18</u>
V10	30	2.5	0.04	6.17	19.65	<u>129.18</u>

cf.) $\sigma_u = F_u / (\pi D t)$

Chapter 3. Residual Ultimate Strength of Pit Corroded Plate

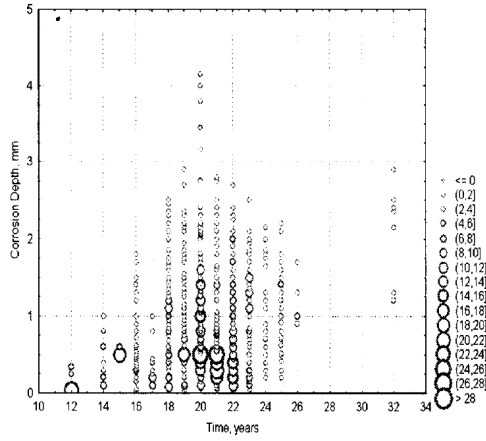
3.1 Introduction

For ship and offshore structures, the maritime environment is heavy corrosive. Corrosion is a very important time dependent phenomenon for ship and offshore structures, especially for aged equipment. Usually, two kinds of corrosion are mainly investigated in previous research, general corrosion and pit corrosion. In the calculation of ultimate strength of plate or shell structures, general corrosion is normally treated as uniform thickness reduction. But the treatment for pitting corrosion is more complicated.

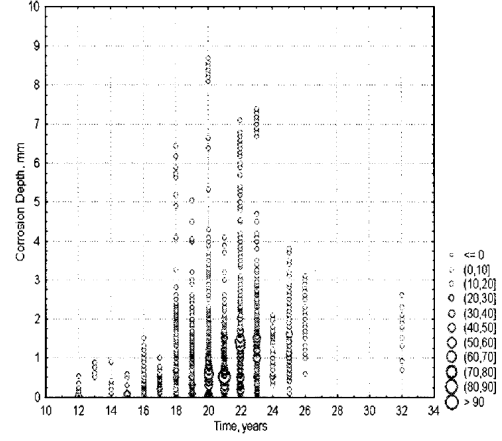
Melchers ^[22, 23, 43-45] has investigated the pit corrosion of mild steel. Both short period (less than 6 months) and long period (7 years) of exposure time is studied. And the influence of water temperature is taken into consideration. Based on the data, a mathematical model is proposed to describe the relationship between pit depth and exposure time.

Garbatov et al ^[24] have also measured the pit depth with the pass of time as shown in Fig. 3.1. Paik et al ^[46] has also measured the corrosion depth data from bulk carriers as shown in Fig. 3.2.

According to the measurement from Garbatov et al ^[24] and Paik et al ^[46], the relationship between pit depth and time exposure varies heavily. That means the corrosive situation changes in a high level. It is reasonable, because the corrosion phenomenon is a complicated issue in maritime environment. It differs from one ocean area to another, from one ship to another and also from one part of the ship to another part. The corrosion level of the structure is affected by too many factors from the corrosive environment, such as the elemental composition of the material, temperature, pH value, salinity, oxygen percentage and water (liquid) flow speed.



Frequency scatter diagram of corrosion wastage of deck plates of ballast tanks



Frequency scatter diagram of corrosion wastage of deck plates of cargo tanks

Fig. 3.1 Corrosion depth measurement data from Garbatov et al [24]

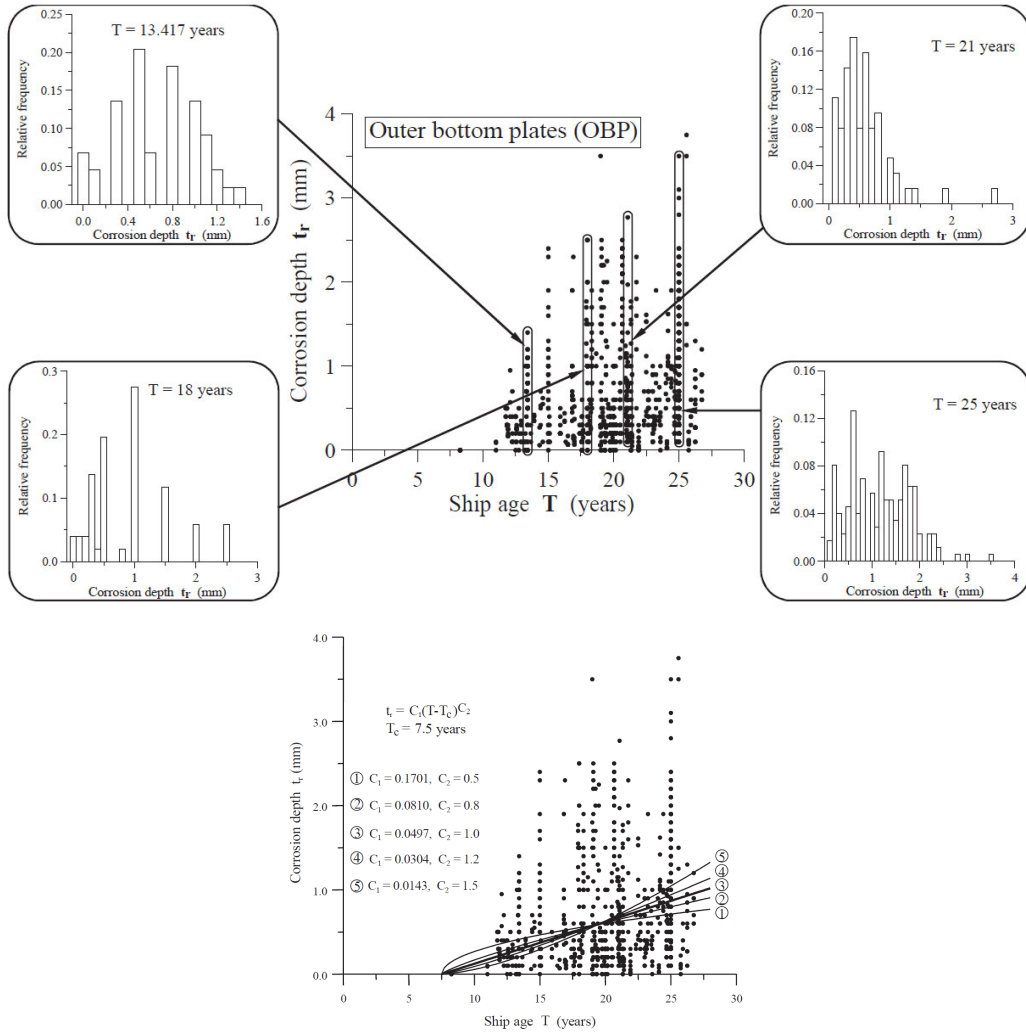


Fig. 3.2 Corrosion depth measurement data and samples of fitting models from Paik et al [46]

Nakai [26, 47-48, 60] has measured the pit shapes in marine structures. He observed the shape of pit corrosion on hold frames of 12, 14 and 20 years-old bulk carriers and a 22 years-old oil tanker. He found that the pit shape is a circular cone and the ratio of the diameter to the depth is in the range between 8 to 1 and 10 to 1 in bulk carriers, and the ratio is in the range between 4 to 1 and 6 to 1 in oil tankers. Based on that, he investigated the compressive and bending loading capacity of corroded plates by model experiments. And numerical calculations are also performed to study the strength of web plates. As a result, the average thickness loss is regarded as a key parameter to affect the residual ultimate strength. It should be mentioned that, in the researches the artificial pits are arranged on both surfaces of the plate. Based on the observation results, plate members with artificial pits on both surfaces is tested by experiments under in-plane compression and bending.

Sumi [27, 49-50] investigated the tension and bending capacity of pit corroded plates. The artificial pit shape is circular cone with the ratio of pit diameter to depth is 8:1. And numerical simulation is performed utilizing the general purpose software LS-Dyna, in which solid element model is used.

Paik [28, 51] proposed a model to describe the relationship between corrosion depth and structure age based on the measurement data. And he investigated the compressive ultimate strength of corroded plate by both experiments and numerical calculations by ANSYS. The pits are simulated by circular holes through the entire thickness of the plate. In the conclusion, a new parameter, i.e. the smallest cross-sectional area, is proposed to represent the ultimate strength reduction characteristics due to localized corrosion.

$$R_{xu} = \frac{\sigma_{xu}}{\sigma_{xio}} = \left(\frac{A_o - A_r}{A_o} \right)^{0.73} \quad (3.1)$$

Where, A_o is the original cross-sectional area,

A_r is the reduced cross-sectional area at the most heavily pitted location

Huang [52] indicated that, the ultimate strength is almost the same despite of the pit shape of cylinder, semi sphere or circular cone, if the material loss volume is the same.

Jiang ^[53] investigated the residual ultimate strength of pit corroded plate under biaxial compression. The plate was simply supported at four edges and pit was assumed to be on both surfaces of the plate. And *DOP* (the degree of pit corrosion intensity defined as the ratio of pitted area to the whole surface area) was chosen as the key parameter to describe the ultimate strength of pit corroded plate under in-plane compression

Zhang ^[54] applied shell elements to model the corroded stiffened plate. It was assumed that, pitting corrosion almost occurred to overall the plate. It was concluded that the *DOP* affected on the ultimate strength of corroded plate. The ultimate strength of corroded plate with the aspect ratio α of 2-7 and slenderness ratio β of 1-4 were investigated.

$$\alpha = \frac{a}{b} \quad (3.2)$$

$$\beta = \frac{b}{t} \sqrt{\frac{\sigma_y}{E}} \quad (3.3)$$

Where, a , b and t are the length, breadth and thickness of the plate, respectively;
 σ_y and E are the yield stress and Young's modulus of the plate material.

However in most of the previous researches, the pit corrosion is assumed to occur on both surfaces of plate symmetrically, which is not close to real cases. Unlike general corrosion, pit corrosion usually occurs locally in plate. Then, *DOP* seems not to be a sufficient parameter to describe the ultimate strength of pit corroded plate.

It is because the corrosion depth is not considered in this parameter, and the overall *DOP* can hardly represent the stress concentration of pit corroded plate exactly. Instead, the maximum reduction of cross section, A_r , is chosen to be the parameter to describe the residual ultimate strength of pit corroded plate, since it could represent the weakest part under axial compression.

One of the purposes of this study is set to be the investigation of the residual ultimate strength of pit corroded tubes. However, on this propose, the modeling of the pit corrosion in the shell FEM modeling and clarify the fundamental effect of the pit corrosion on the compressive

behavior of shell structures, a pit corroded plate under compression is targeted and its behavior is investigated.

In this chapter, the pit shape is assumed to be conical by referring to Nakai ^[26] and nonlinear FEM software MSC.Marc is applied for numerical simulations for estimating the residual ultimate strength of corroded plate. In order to calculate more effectively, a method in which the corroded plate is modeled by shell elements is proposed, firstly.

Secondly, several potential influential effects on the residual ultimate strength of pit corroded plate, such as effect of pit shape, pit size, corroded area location, corroded area size and the slender ratio of plate thickness to breadth, are studied. Then the coupling effect of the above is clarified by calculating the residual ultimate strength of pit corroded plate.

Moreover, in order to represent the effect of A_r for the plate with different thickness, the concept of ‘the equivalent reduction of cross section ($A_{r,eq}$)’ is introduced. Finally, the relationship between the residual ultimate strength and $A_{r,eq}$ is derived by a simplified formula.

3.2 A method to model pit corroded plate by shell element

To model pit corroded plate, both solid and shell elements are applicable in FEA. The behaviors of thin or thick plates at their ultimate state are different. The ultimate state for thick plate with small slenderness ratio β is plastic yielding, and that for thin plate with large slenderness ratio β is elastic buckling ^[66].

So the comparison of both thick and thin plate with pits is performed. In solid element models, the corroded plate can be modelled with the exact configuration by using several elements in thickness direction. To maintain the calculation accuracy, the aspect ratio of the elements between thickness, length and breadth had better to be nearly 1.0. In this case, too many elements are necessary. Fine meshed model using solid elements with exact pit shape is shown in Fig. 3.3. In order to reduce calculation time, only a quarter of plate is modelled by solid elements.

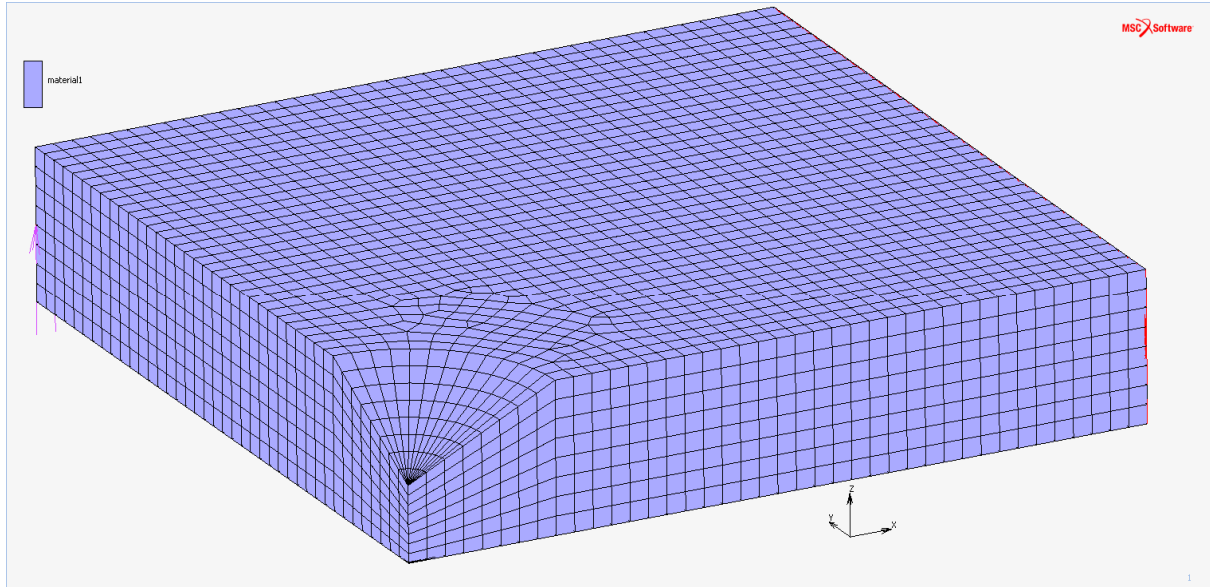
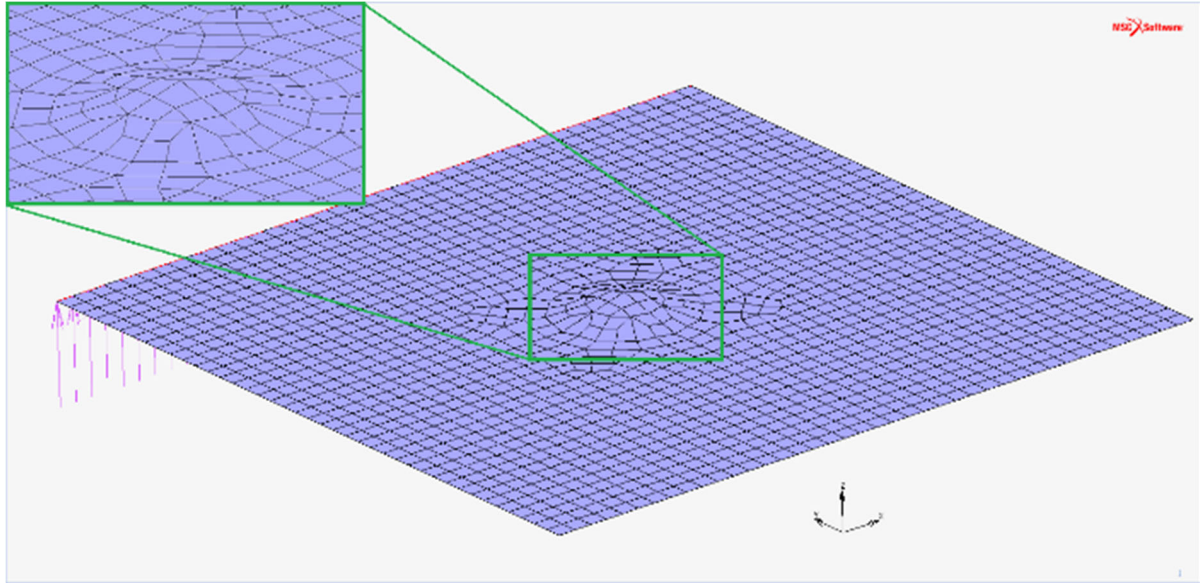


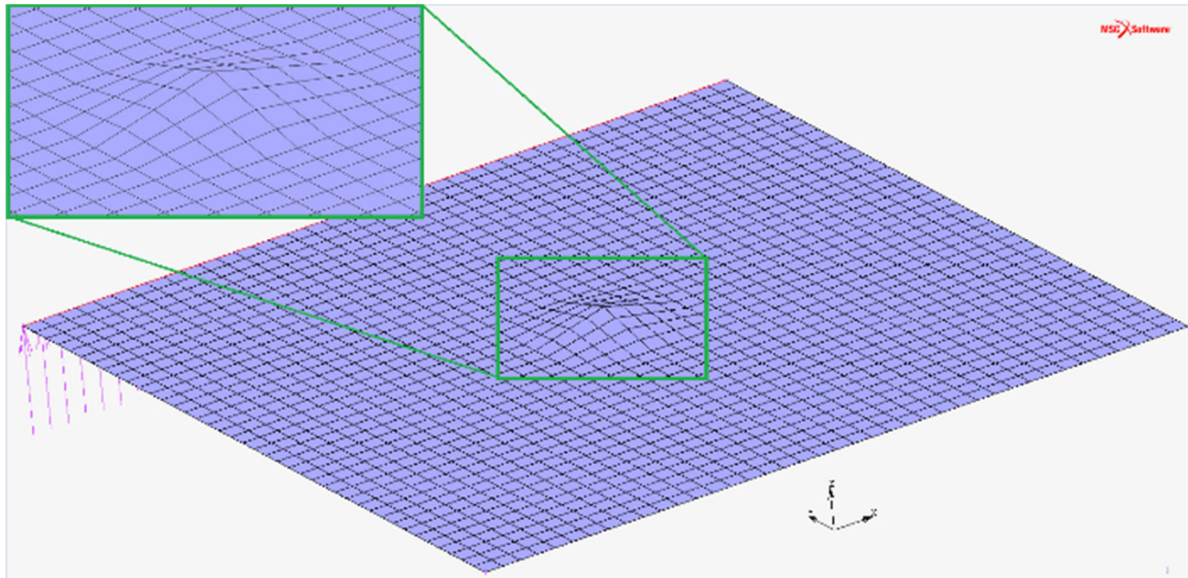
Fig. 3.3 Calculation model using solid elements for conical pit

For the sake of reducing computational time, the use of large sized shell element is required. In order to obtain calculation results rapidly, two kinds of methods are examined to model the corroded plate by shell element. One is the shell element model with conical pits (exact shape, hereinafter called as circular pit) as shown in Fig. 3.4 (a). The other is the shell element model with quadrangular pyramid pits (assumed shape, hereinafter called as rectangular pits) as shown in Fig. 3.4 (b). The change of neutral plane in thickness direction is realized by moving the nodes in the thickness direction, which means changing the z -coordinate of the nodes within the corroded area.

In order to avoid the error resulted from very large aspect ratio of shell elements, extra time is necessary to create the mesh division for a circular pit, and it is shown in the detail of Fig. 3.4 (a). However, for rectangular pit, the mesh division is easier than that for circular pit as shown in Fig. 3.4 (b). In this model, the pit shape is concerted to rectangular and the thickness distribution for elements within corroded area is assumed as shown in Fig. 3.5. In this model, the length of assumed rectangular pit is set equal to the diameter of exact circular pit. The pit depths are the same in both models. By adopting the above procedure, it is easy to model the rectangular pits by rectangular shell elements. Meanwhile, the shape of corroded part is not the same as exact one. Therefore the modeling errors in estimation of residual ultimate strength must be checked.



(a) Shell model for circular pit



(b) Shell model for rectangular pit

Fig. 3.4 Calculation models using shell elements for circular and rectangular pits

The calculations for the corroded plates under compression in both plastic yielding and elastic states were performed and the calculated ultimate strength using solid model and two kinds of shell models were compared. The plate material is mild steel, in which yield stress and Young's modulus are 235MPa and 2.1×10^5 MPa, respectively. The initial imperfection mode is the buckling mode (sinusoidal mode), and w_0 is the maximum amplitude of imperfection.

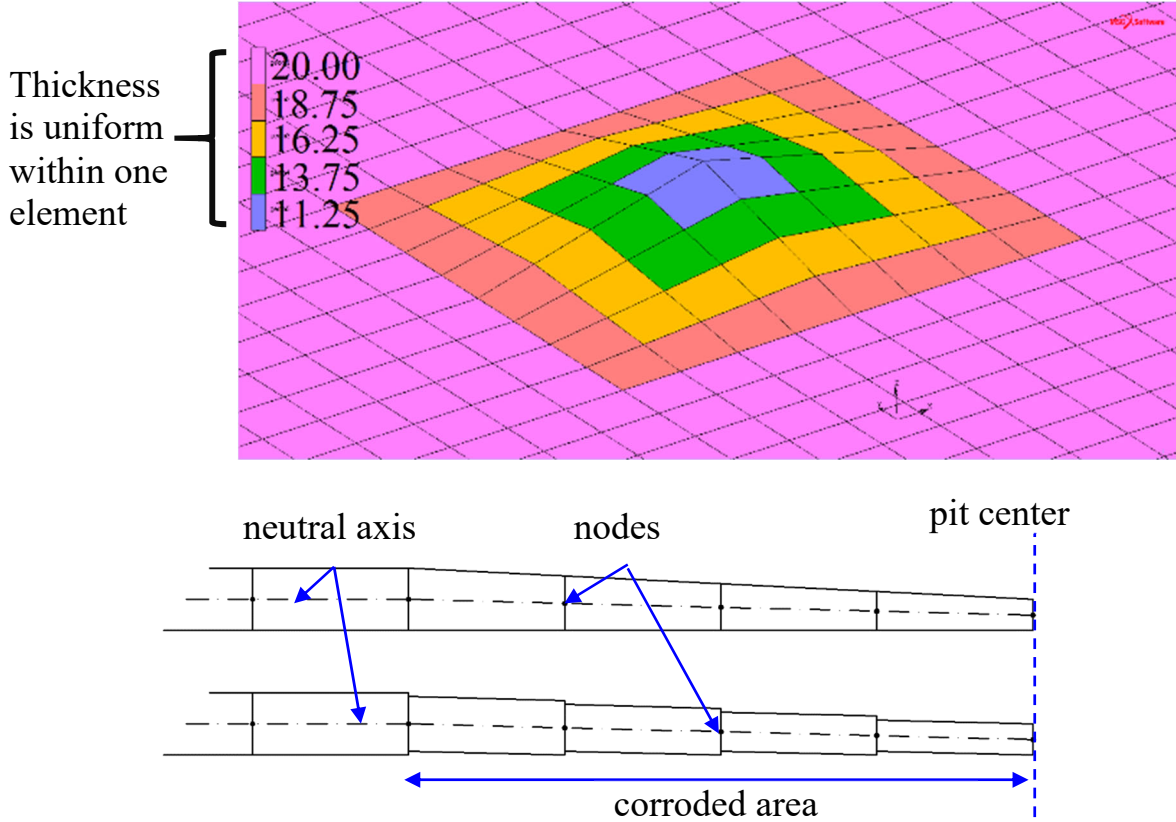


Fig. 3.5 Assumed thickness distribution for rectangular pit using shell elements ($t=20$ mm)

In order to confirm the validity of this method no matter the ratio of pit shape with different ratio of pit size (l) to pit depth (d), a quarter part of a plate is modelled considering the symmetry of deformation, as shown in Fig. 3.6. The size of this plate is 800×800 mm. This plate is simply supported in all four edges. The pits are arranged uniformly distributed in the middle span of the plate along the loading direction (x direction). For comparison, the exact shape (circular cone) of pit corrosion was model in solid element models.

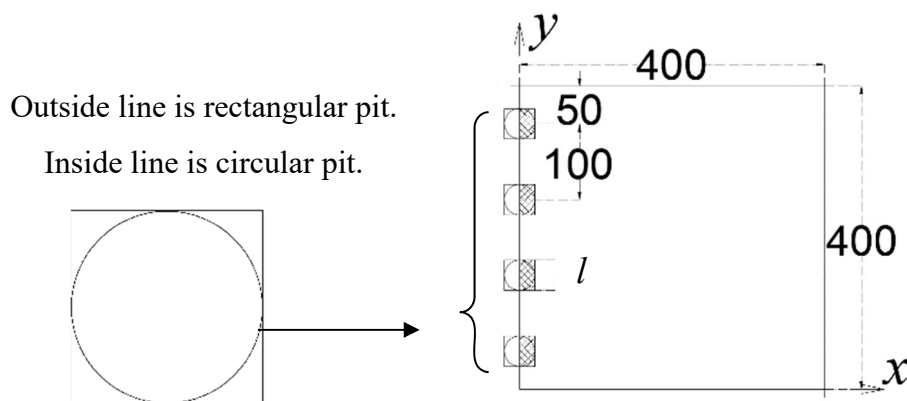


Fig. 3.6 Pits positions and plate size of the quarter corroded plate

The pit shapes are shown in Table 3.1. The first number of case ID shows the thickness of plate (mm), and the second number shows the length and breadth of pit, and third number means the depth of pit. Both of 10 and 20 mm thickness plates are modelled for examining the behavior of plastic yielding and elastic buckling, respectively. The geometrical initial imperfection of buckling mode is introduced into the model, as follows,

$w = w_0 \sin(\frac{\pi x}{a}) \sin(\frac{\pi y}{b})$. w_0 is the amplitude of the geometrical initial imperfection. For $t=10\text{mm}$, $w_0=0.1t=1\text{mm}$. For $t=20\text{mm}$, $w_0=0.01t=0.2\text{mm}$.

Table 3.1 Pit shapes on the corroded plate

Case	t (mm)	l (mm)	d (mm)	l/d
10-20-5	10	20	5	4
10-80-5	10	80	5	16
20-40-10	20	40	10	4
20-80-5	20	80	5	16

Fig. 3.7 shows the relationship between average stress and global strain, and Fig. 3.8 shows the relationship between average stress and deflection at plate center. The average stress is calculated to be the reaction force divided by the initial cross section area. The global strain is the calculated to be the uniform enforce displacement divided by the length of the plate. And the grey solid line is the yield stress of material.

From the above calculation results, the effectiveness of shell element model by assuming the rectangular shaped corrosion instead of real circular shaped corrosion is confirmed in both thin and thick plates. Seeing the calculation results in Fig. 3.7, in the cases of the ultimate strength of thin plate ($t=10\text{mm}$), the elastic buckling takes place at the average stress of 150MPa, and then the plastic yielding takes place by adding the bending stress due to out of plane deformation to compressive stress, and finally shows the peak stress. In the case of the thick plate ($t=20\text{mm}$), the ultimate strength is almost the level of the yield stress. It means that the plate yields mainly due to compressive stress without lateral deformation (seeing Fig. 3.8).

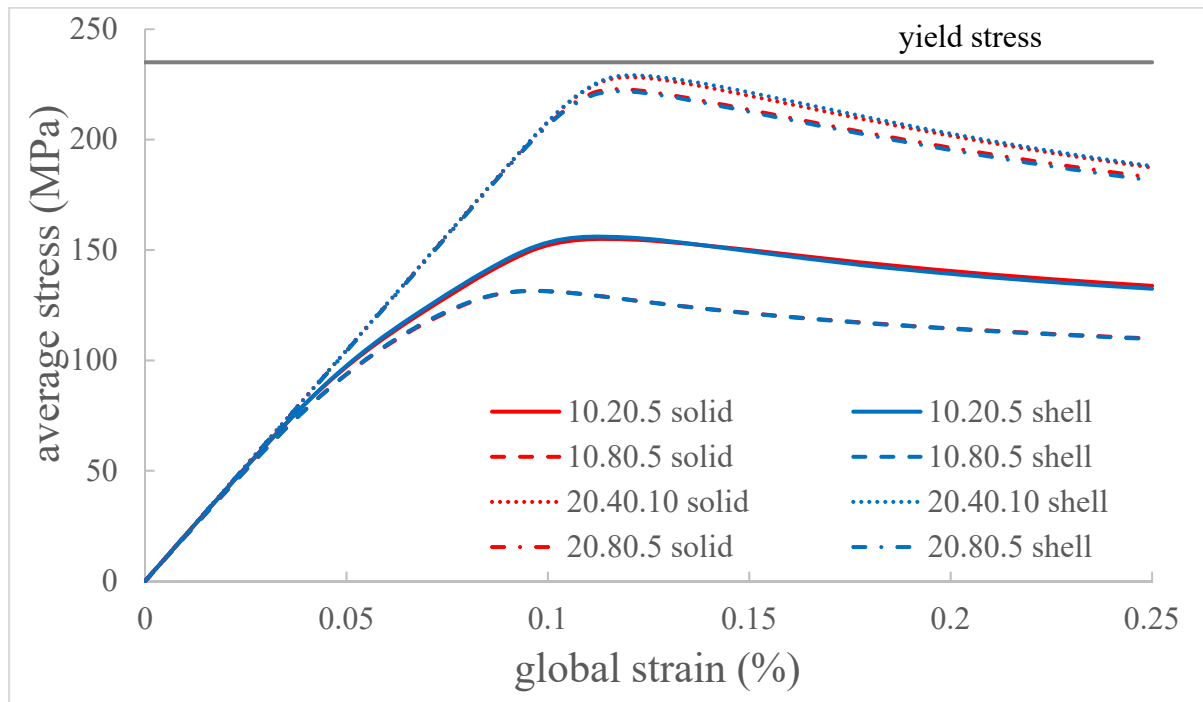


Fig. 3.7 Relationship between average stress and global strain of corroded plate with different pit shapes (comparison between solid model and shell model for plate with the size of 800×800mm)

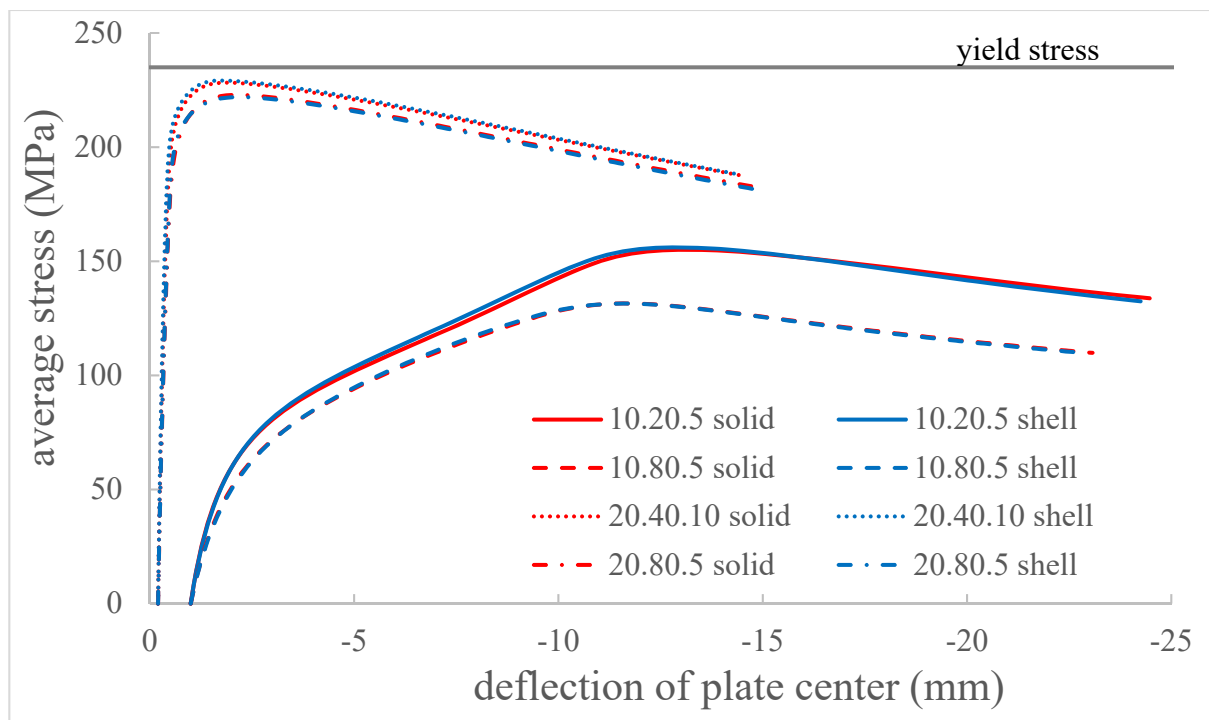


Fig. 3.8 Relationship between average stress and deflection at plate center of corroded plate (comparison between solid model and shell model for plate with the size of 800×800mm)

The effect of geometrical initial imperfection is larger in the thin plate than the thick plate in this thickness range. It is because the lateral deflection before ultimate strength in the thin plate is larger than the thick plate. The difference of results between the solid model and the shell model is small enough.

3.3 The effects of pit corrosion factors

Pit corrosion produces complicated collapse behavior of steel plates. Many factors may have influence on the residual ultimate strength of pit corroded plate, such as the pit shape, ratio of plate length to breadth, the position of corroded area on the plate and the size of the corroded area. In this section, effects of all these factors are tested, and then the dominant one is pointed out.

3.3.1 The effect of pit shapes

As described in the previous section, it is confirmed that the proposed method using rectangular pit is valid to calculate the residual ultimate strength of corroded plate by shell elements. In the above comparison between solid element model and shell element model, good agreement is achieved. In the shell element model, 4 meshes is applied from center to edge pit corrosion.

The effect of ratio of pit length to depth (l/d in Fig. 3.9) on the residual ultimate strength of plate is investigated. The calculated plate is a square plate with 800mm length supported along all four edges. The uniform compressive displacement is imposed in x direction. To reduce calculating time, only a quarter of the plate is modelled. Two kinds of thicknesses are selected, 20mm and 10mm. The maximum initial geometrical imperfection is 1% of thickness for $t=20\text{mm}$, 10% for $t=10\text{mm}$. Five kinds of ratio l/d are selected for both plate thicknesses, as shown in Table 3.2 and Table 3.3. In both thicknesses, the plates with different pit shapes have the same cross section area reduction. The reason why the geometrical initial imperfection is different for thick and thin plate is based on two opinion. One is that the allowance maximum initial deflection existed on plate members is different for plates with different thicknesses, lager value of initial deflection is allowed to occur on plate with smaller thickness. The other is because the ultimate state of plates with different thicknesses is not the same. For thick plate,

the ultimate state yielding which is limited by material yield stress. For thin plate, the ultimate state is buckling which is highly influenced by the initial deflection. In order to avoid changing the ultimate state of the plate, a small value of geometrical initial imperfection amplitude is introduced to thick plate.

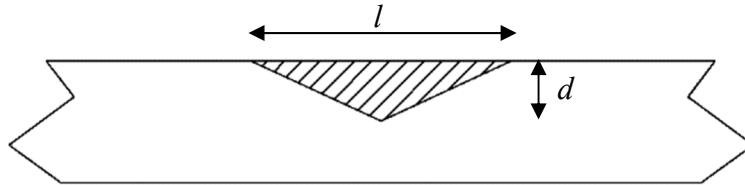


Fig. 3.9 Pit shape: length (l) and depth (d)

Table 3.2 Calculation cases for the plate of $t=20\text{mm}$ with geometrical imperfection $w_0/t=0.01$
(calculation parameter is pit length and depth)

Case	l (mm)	d (mm)	l/d	Ultimate strength (MPa)
intact	-	-	-	234.3
20-10	20	10	2	228.9
25-8	25	8	3.125	226.5
30-6.67	30	6.67	4.5	224.7
40-5	40	5	8	222.3
50-4	50	4	12.5	221.1

Table 3.3 Calculation cases for the plate of $t=10\text{mm}$ with geometrical imperfection $w_0/t=0.1$
(calculation parameter is pit length and depth)

Case	l (mm)	d (mm)	l/d	Ultimate strength (MPa)
intact	-	-	-	157.8
10-5	10	5	2	155.2
12.5-4	12.5	4	3.125	154.6
15-3.33	15	3.33	4.5	154.0
20-2.5	20	2.5	8	153.0
25-2	25	2	12.5	152.3

As shown in Fig. 3.10, 8 and 16 pits are modeled at middle of plate length equably along the breadth direction for $t=20\text{mm}$ and $t=10\text{mm}$, respectively. So the reduction of cross section in both cases is 10% of the initial section area. Fig. 3.11 and Fig. 3.12 show the calculation results of average stress-global strain relationship with different pit shapes for thick and thin corroded plate, respectively. The first number of case ID shows the length and breadth of pit, and the second number means the depth of pit.

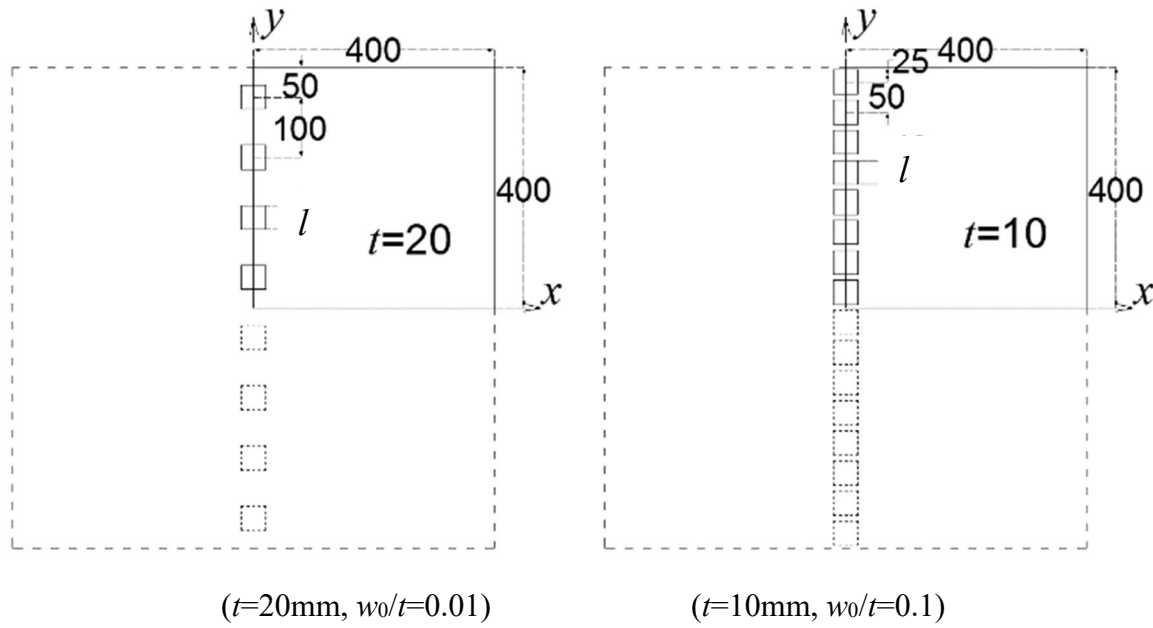


Fig. 3.10 Pit position and numbers for plates with same cross section reduction with different pit shapes

From the calculation results, it is found that the reduction of ultimate strength of corroded plate from intact plate is a little larger in the case of large ratio of pit size to depth. The reason is as follows. All five pit shapes share the same cross section reduction area, but the large value of pit length “ l ” means longer corrosion size in plate length because “ l ” means the size of pit both in breadth and length. It might influence on the ultimate strength of corroded plate.

In considering the safety side of residual ultimate strength of corroded plate, the large length of pit is arranged on the plate in the following calculations.

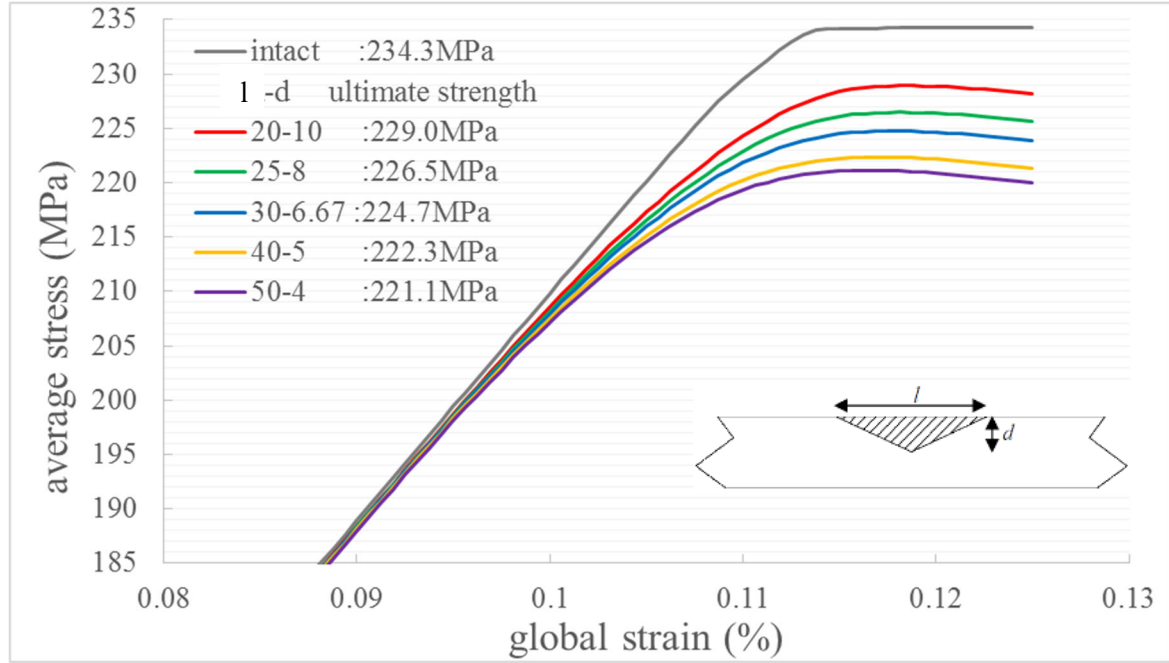


Fig. 3.11 Relationship between average stress and global strain of corroded plate (comparison between different ratios of pit length to depth with same cross section reduction, $t=20\text{mm}$, $w_0/t=0.01$)

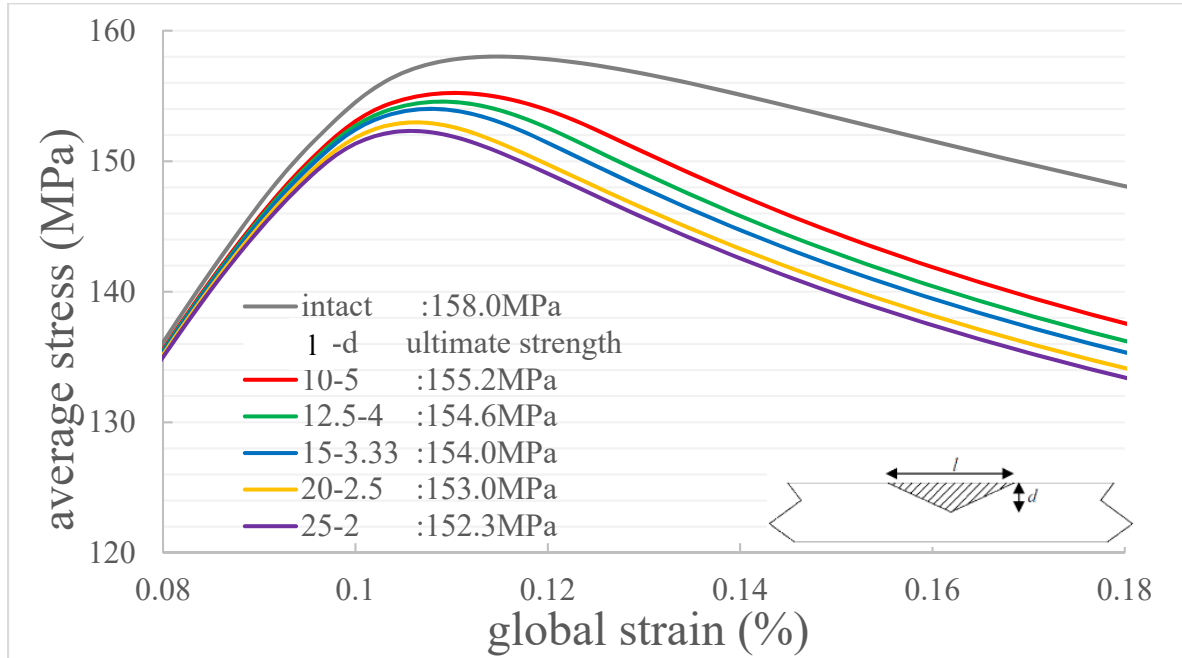


Fig. 3.12 Relationship between average stress and global strain of corroded plate (comparison between different ratios of pit length to depth with same cross section reduction, $t=10\text{mm}$, $w_0/t=0.1$)

The differences between the residual ultimate strength of corroded plates with different shaped pits are tiny as shown in Fig. 3.11 and Fig. 3.12. In order to make it clear that the effect of pit shapes has almost no influence on the residual ultimate strength of corroded plate if the corroded area is in the same size, a pit corroded plate of size $2400 \times 800 \text{ mm}$, $t=10 \text{ mm}$ & 20 mm is modelled as shown in Fig. 3.13. The plate is simply supported and suffers from uniform axial compression. Only the shadowed a quarter is modelled by considering the symmetry of deformation. So the boundary condition is as follows,

AB: displacement in y direction is fixed;

CD: rotation about x axis is fixed, and displacement in y direction is uniform;

AD: displacement in x direction is fixed;

BC: rotation about y axis is fixed, and displacement in x direction is uniform enforce displacement.

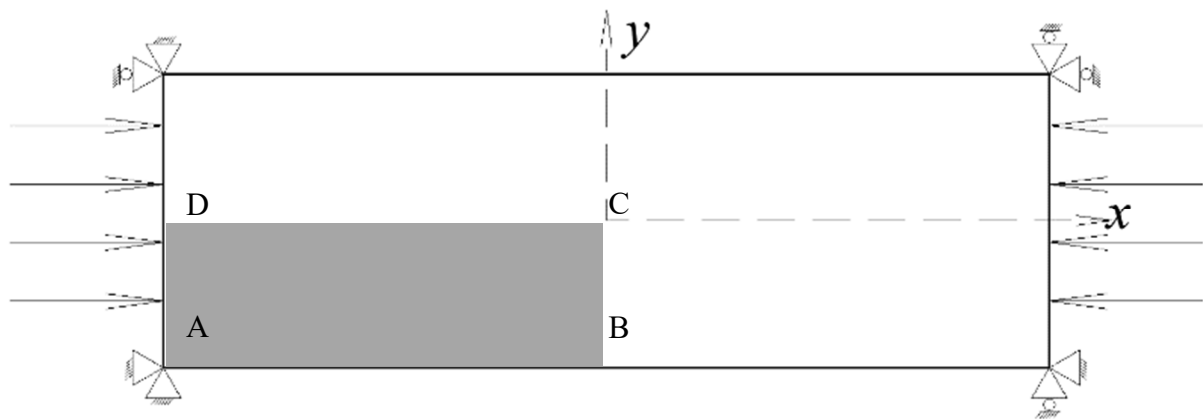
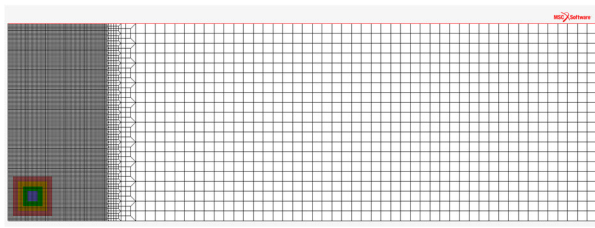


Fig. 3.13 Simply supported boundary condition

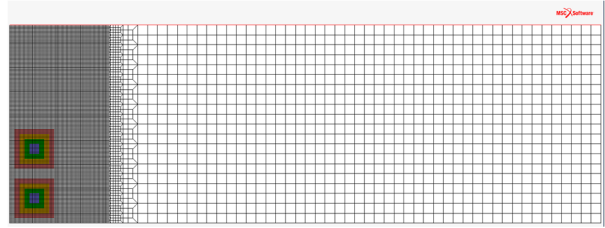
The detail of corroded area is shown in Fig. 3.14. Pit corroded area locates on the surface of the left side of plate. The mesh size is $2.5 \times 2.5 \text{ mm}$. And the pits shapes are shown in Table 3.4, r is the half size of pit, $l/2$. And the calculated results of relationship between average stress and globe strain are shown in Fig. 3.15 and Fig. 3.16 for thick and thin plate, respectively. Case ID of 'r20 2×4' means the pit size is 40 mm , and the pit arrangement is 2 lines of pits in x direction and 4 lines of pits in y direction (see Fig. 3.14).

Table 3.4 Ratios of pit length to depth

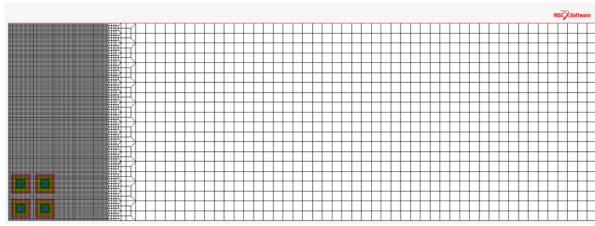
Case	r (mm)	d (mm)	l/d ($t=20\text{mm}$ or 10mm)
r40	40	$0.5t$	8 or 16
r20	20	$0.5t$	4 or 8
r10	10	$0.5t$	2 or 4



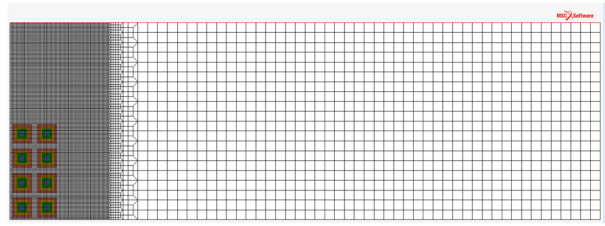
(r40-1×1)



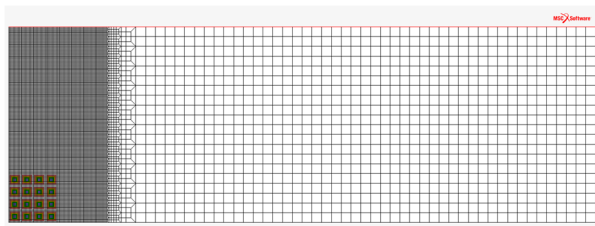
(r40-1×2)



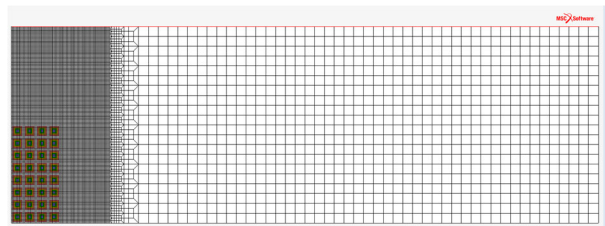
(r20-2×2)



(r20-2×4)



(r10-4×4)



(r10-4×8)

Fig. 3.14 Detail pit position arrangements of different pit shape with same corroded area size

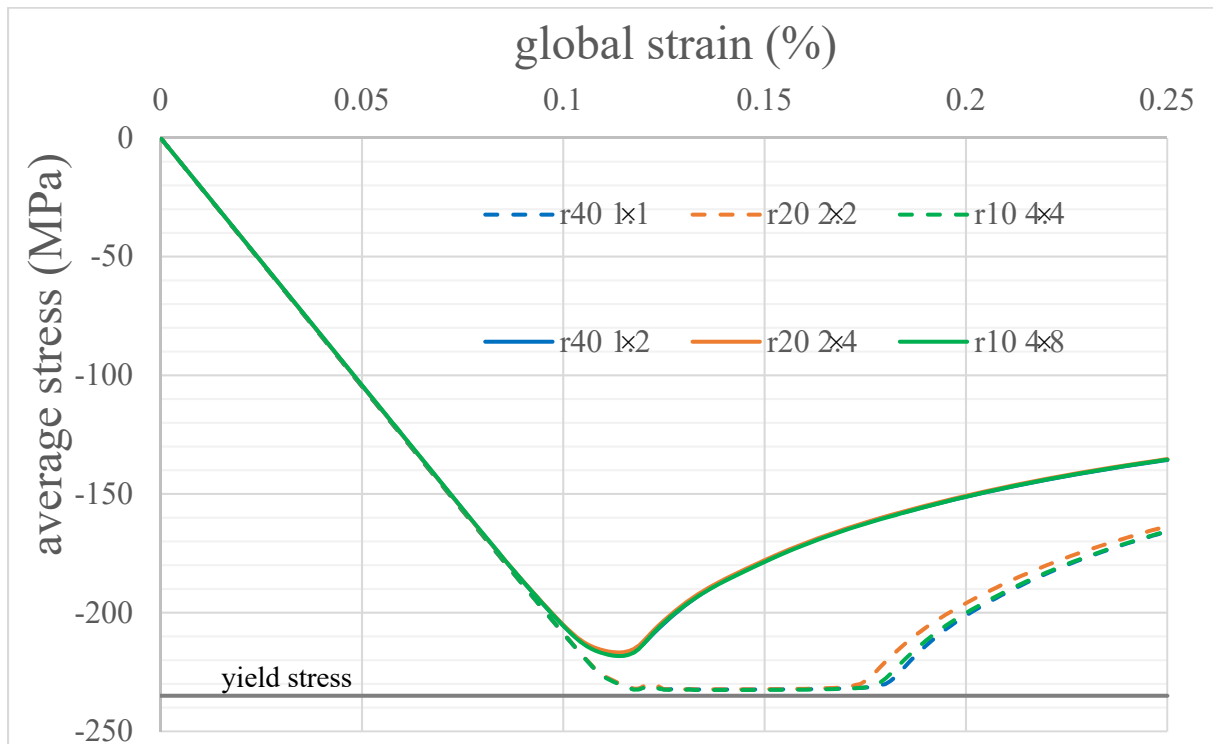


Fig. 3.15 Comparison of relationship between average stress and global strain of pit corroded plate of different pit shapes with same corroded area size ($t=20\text{mm}$, $w_0/t=0$)

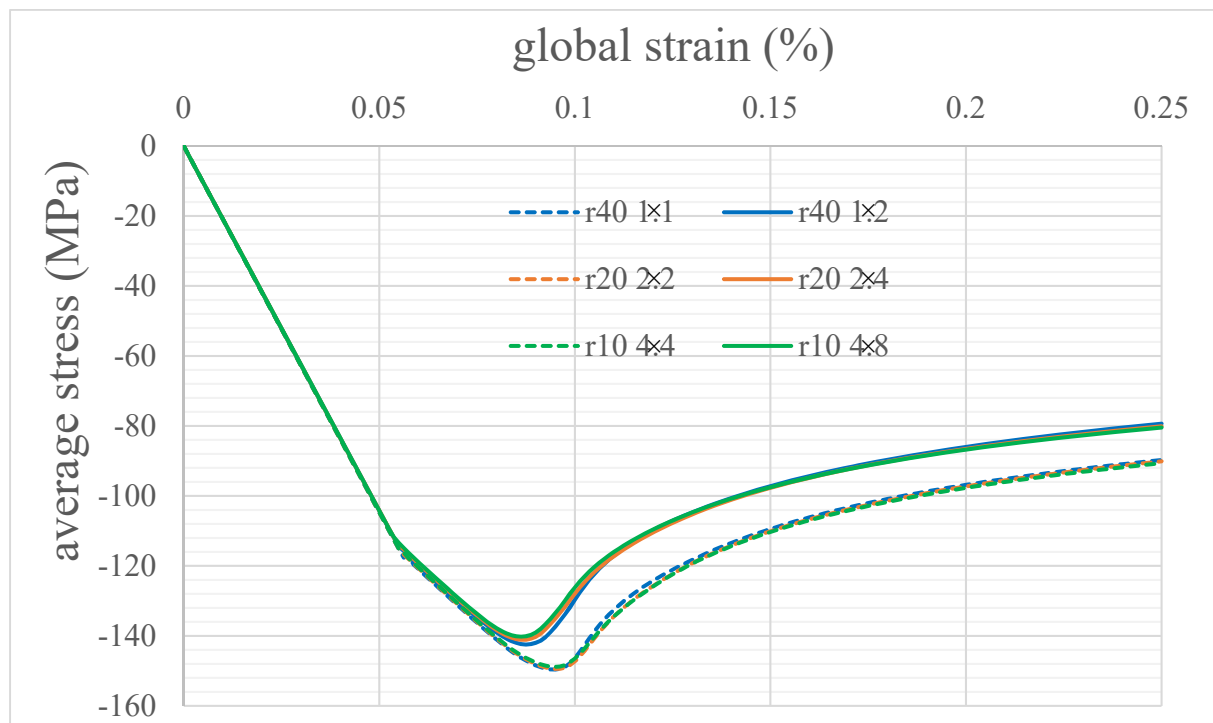


Fig. 3.16 Comparison of relationship between average stress and global strain of pit corroded plate of different pit shapes with same corroded area size ($t=10\text{mm}$, $w_0/t=0$)

And from the results, it is found that the residual ultimate strength of different shaped pit corroded plates is almost the same if the corroded area size is the same. Not only the peak value but also the post ultimate behavior shows the same tendency. That means if the corroded area position, corroded area size both in length and breadth and pit depth are all the same, the residual ultimate strength is the in the same level, despite of the pit shape. As a result, application of artificial pit with different ratios of pit size to depth will not influence on the accuracy of numerical simulation results when the corroded area size is the same.

The mesh division of numerical model is decided by the real structure. Eight shell elements is needed in this research to model one pit. As it is confirmed that pit size is has no influence, so large size of shell element could be applied in the following calculations.

3.3.2 The effect of corrosion position

Pit corrosion might occur to any part of the plate. In order to figure out the most severe case, the position effect of corroded area is investigated. In the following calculations, a rectangular plate with length $a=2400\text{mm}$ and breadth $b=800\text{mm}$ is selected as the calculating model by changing the plate thickness t . This size of plate is typical in marine structures. The plate is assumed to be simply supported along all four edges. The compressive load is imposed by uniform enforce displacement along the short side of the plate. That means the plated is compressed in the longitudinal direction (x -direction in Fig. 3.13). The elastic buckling stress of this plate without imperfection is as follow,

$$\sigma_{cr} = k \frac{\pi^2 E}{12(1 - \nu^2)(b/t)^2} \quad (3.4)$$

Where k is 4.0 for all edge simply supported flat plate;

ν is the Poisson ratio of material.

When $t=14\text{ mm}$, the elastic buckling stress σ_{cr} equals to σ_y (235MPa). So in this research, two kinds of plate thicknesses are selected in calculations, 10mm (for elastic buckling), and 20mm (for elasto-plastic buckling).

The following initial geometrical imperfection is introduced into the plate,

$$w = w_0 \sin(m\pi x/a) \sin(n\pi y/b) \quad (3.5)$$

Where, w_0 is the maximum amplitude of imperfection;

$m=3$ and $n=1$ are chosen, considering the buckling mode of the plate under longitudinal uniform compression.

As shown in Fig. 3.17, three different positions of corroded area, #0, #400 and #1000, are chosen in the plate length, which means that the distance from the corroded area center to the plate center is 0, 400, and 1000mm, respectively. And two different positions in breadth, C and E, are chosen, that means the central corrosion and the edge corrosion. Each corroded area contains 16 pits. Each pit has the length of 80mm and the depth of $0.5t$. The maximum initial geometrical imperfection, w_0 , is 10% of plate thickness. For the intact case, the plate is without corrosion but with initial geometrical imperfection.

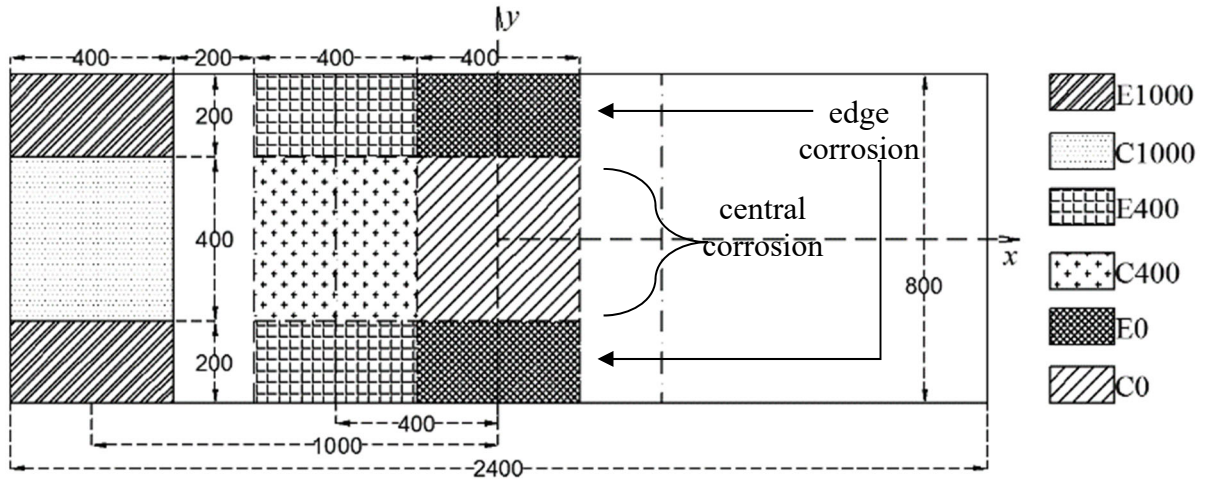


Fig. 3.17 Assumed positions of corroded area in plate ($t=10\text{mm}$ & 20mm , $w_0/t=0.1$, $l=80\text{mm}$, $d=0.5t$)

The calculation results are compared with each other in Fig. 3.18 and the obtained ultimate strength in Table 3.5. For both thin ($t=10\text{mm}$) and thick ($t=20\text{mm}$) plates, when the corroded part locates near the short edge (C-1000 and E-1000), the residual ultimate strength is lowest among all cases. With the central and the edge corrosion in breadth, the tendency is different

for thin and thick plate. For thin plate, the edge corrosion has more effect on the ultimate strength than central corrosion.

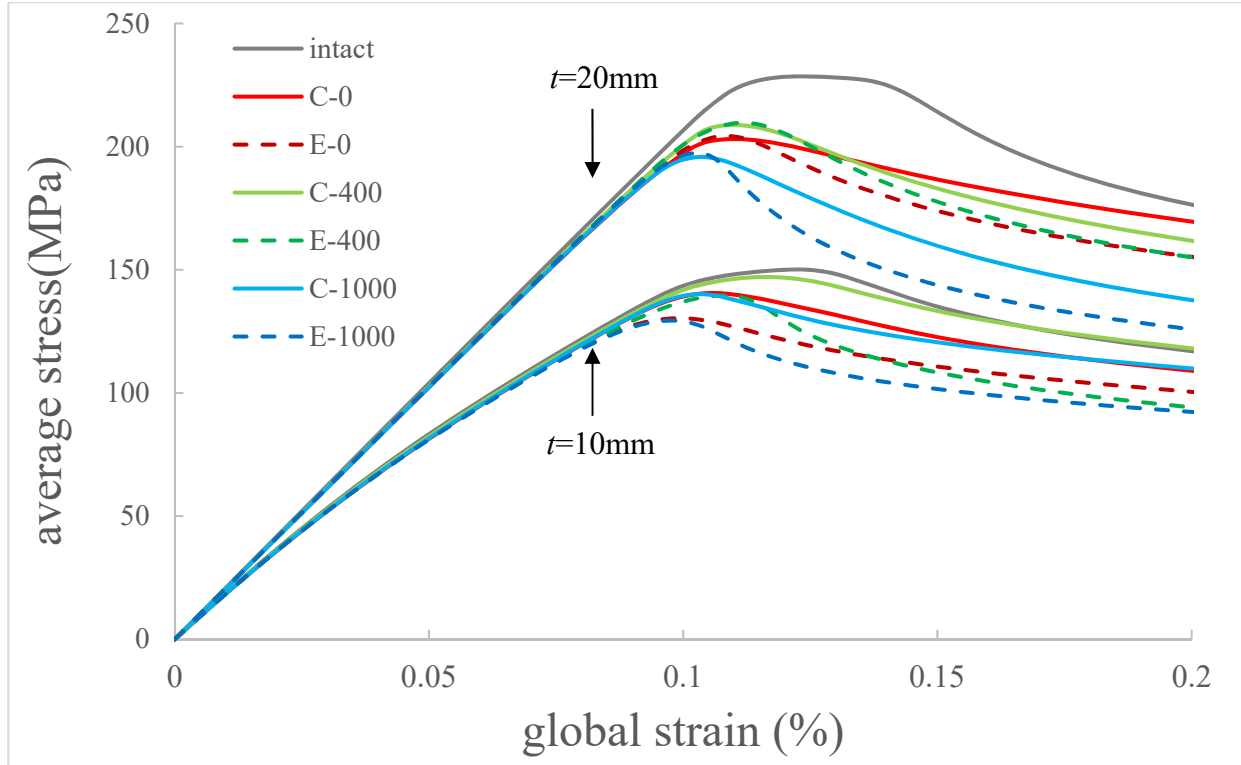


Fig. 3.18 Relationship between average stress and global strain of corroded plate
(comparison between different positions of corroded area, $w_0/t=0.1$)

Table 3.5 Results of ultimate strength (comparison of ultimate strength of corroded plate with
different positions of corroded area, $w_0/t=0.1$)

Case	Ultimate strength (MPa)	
	$t=10$ mm	$t=20$ mm
intact	157.8	228.6
C-0	140.6	203.1
E-0	130.4	204.4
C-400	147.1	208.8
E-400	139.6	209.7
C-1000	140.1	195.8
E-1000	129.4	197.4

The reason is that, from the point view of 'effective width', the edge part of plate plays an important role to resist axial load, and the corrosion will reduce the load carrying capacity of this part. So the edge corrosion gives severer effect on the ultimate strength. For thick plate, the effective width is the whole breadth of the plate, but the central part of the plate is with larger initial deflection due to the geometrical imperfection. Corrosion in this part has larger eccentricity of the neural axis from the loading. But the residual ultimate strength difference between both positions is quite small. Moreover, when considering the post buckling behavior, the corner part (E-1000) of corrosion is regarded as the most severe situation. For both of thick and thin plate, the post buckling strength of edge corroded plates is lower than that of center corroded plates.

Another phenomenon is that the residual ultimate strength of C/E1000 case is smaller than C/E400 case. The reason is that if the corroded area locates close to the corner, the plate boundary has to keep straight since the simply supported. So the restrict condition for corroded area is more rigid. So in the following calculation cases, the corroded position is selected to locate on the corner of the plate.

3.3.2.1 The effect of interaction corroded locations

First, in order to confirm that the separate multiple corroded areas have almost no interaction on the residual ultimate strength of plate, a series calculation was performed. As shown in Fig. 3.19, four cases are calculated, single area A, B, C and combined areas of A, B and C. Plate size is 2400×800×10mm. Each area contains 4 pits with length of 80mm and depth of half of plate thickness. The calculation results of average stress-global strain relationship are shown in Fig. 3.20 and the obtained ultimate strength is shown in Table 3.6.

Among the ultimate of Case A, B and C, the case of the lowest ultimate strength is Case C in both cases of thickness (10mm and 20mm). It was confirmed again that the corner corrosion gives the lowest ultimate strength among the same level of corrosion.

When comparing the case C and Case A, B & C, the ultimate strength of both cases shows almost same. From above, it can be concluded that, if the plate is corroded in several parts

separately, the most severe one has dominant effect on the residual ultimate strength of the corroded plate.

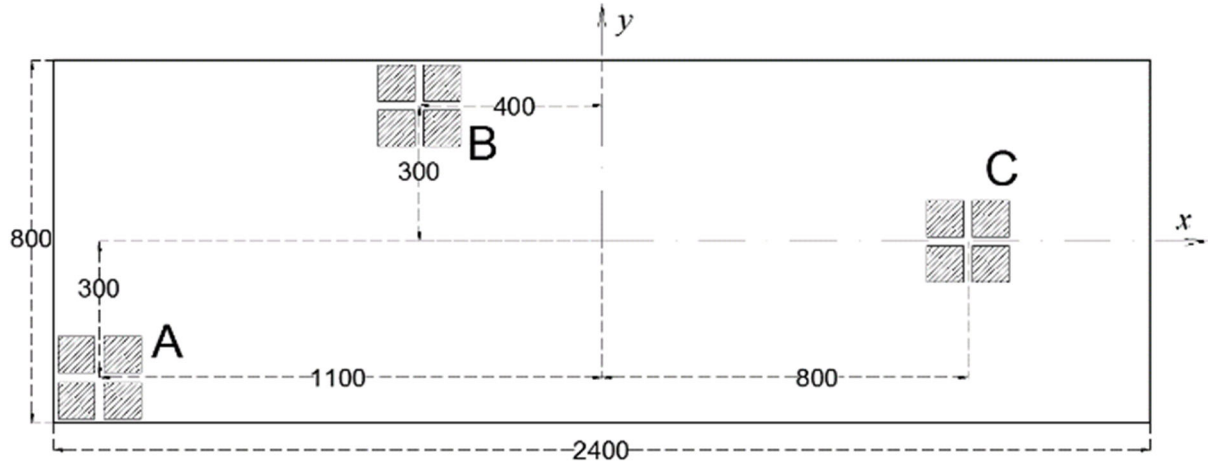


Fig. 3.19 Position of assumed corroded areas (single location of corroded areas or multiple location of corroded areas, $t=10\text{mm}$ or 20mm , $w_0/t=0.1$, $l=80\text{mm}$, $d=0.5t$)

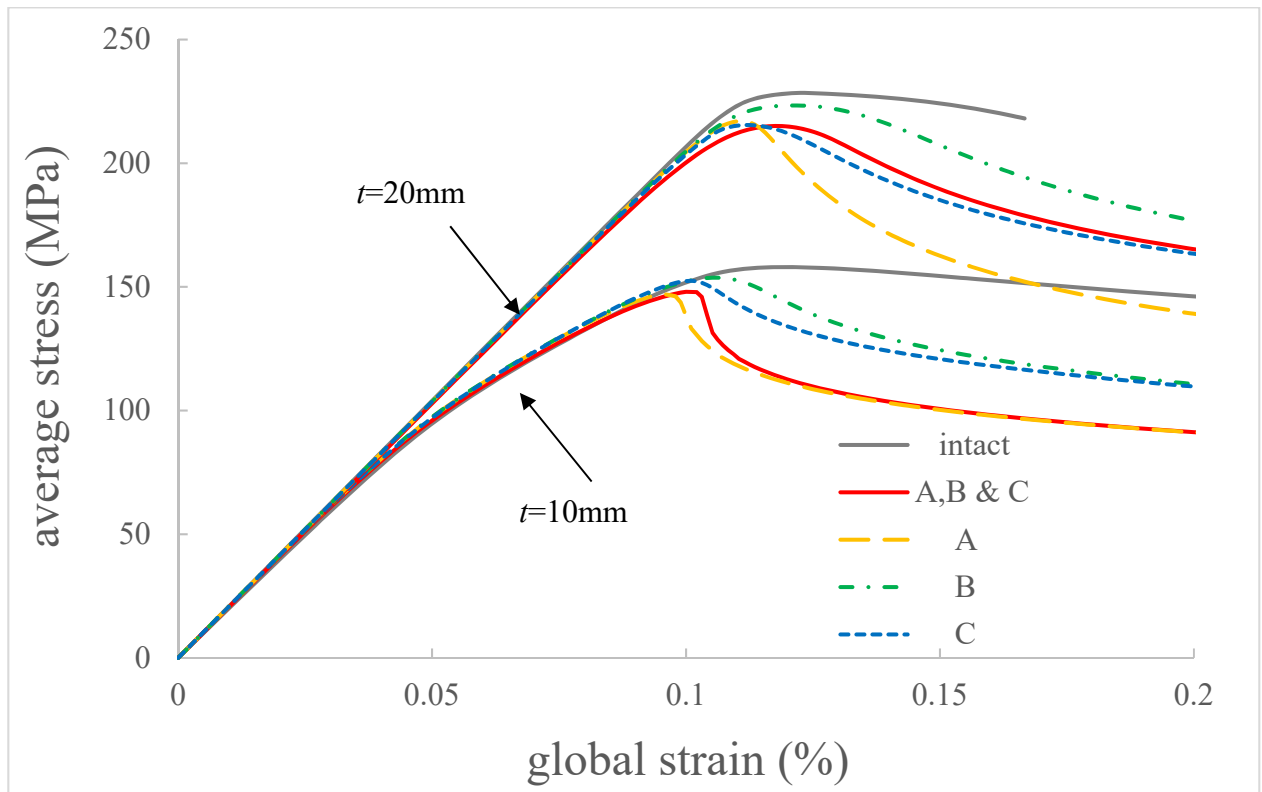


Fig. 3.20 Relationship between average stress and global strain of corroded plate (comparison between single location of corroded areas or multiple location of corroded areas, $t=10\text{mm}$ or 20mm , $w_0/t=0.1$)

Table 3.6 Results of ultimate strength (comparison of corroded plate with single corroded areas or multiple corroded areas, $w_0/t=0.1$)

Case	Ultimate strength (MPa)	
	$t=10\text{mm}$	$t=20\text{mm}$
intact	157.8	228.4
A	147.0	217.1
B	153.7	223.3
C	152.5	215.4
A,B & C	148.0	215.1

3.3.3 The effect of ratio of plate length to breadth

As it is illustrated in the introduction, the ratio of plate length to breadth, $\alpha=a/b$, is in the range of 1-7 for marine structures. In this section, five cases, shown in Table 3.7, are selected to investigate the effect of α on the residual ultimate strength of pit corroded plate.

Table 3.7 Plate scantlings details for the effect of ratio of a/b

Case	a (mm)	b (mm)
$a/b=1.5$	1200	800
$a/b=2$	1600	800
$a/b=2.5$	2000	800
$a/b=3$	2400	800
$a/b=4$	3200	800

Full size of plate is modelled. Both $t=10\text{mm}$ and 20mm cases are calculated. No initial geometrical imperfection is introduced. Pit size is 80mm , pit depth is 50% thickness. Corroded area is the corners of plate as shown in Fig. 3.21. The comparison of calculation results of relationship between average stress and global strain is shown in Fig. 3.22.

As for the residual ultimate strength, the influence of α ($=a/b$) on the ultimate strength of corroded plate is limited, then the effect of ratio of plate length to breadth could be neglected.

As for the post buckling behavior, some difference can be observed. The deflection of corroded plate is localized at the vicinity of corroded part after peak load. Because of reduction of compressive stress due to increase of deflection at corroded part, the deflection of rest part of plate will be reduced. In the case of long plate, the rest part of plate is relatively long, then, the difference of global compressive strain (in other words, average strain) in post buckling range can be seen, although the deflection of corroded part is almost the same among all cases.

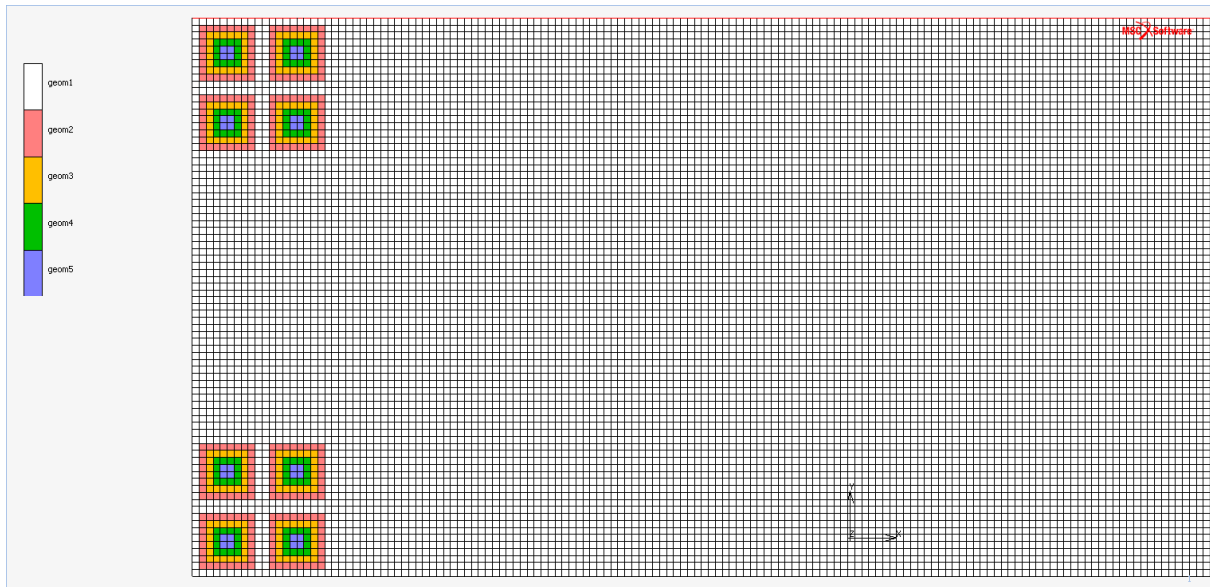


Fig. 3.21 Corner corroded plates with different ratio of α

The stress distribution is shown in Fig. 3.23, the ultimate strength for corroded plates with different ratio of a/b is the same. But the post ultimate behaviors are different. The reason is that, after the ultimate state, the deflection is concentrated in the corroded part. So the collapse is concentrated also in the corroded parts. So the stress-strain curve drops quicker for plate with larger ratio of a/b .

3.3.4 The effect of corroded pit size in length direction of plate

The effect of size of corroded areas in length is investigated here. As shown in Fig. 3.24, a quarter of whole plate is modelled with initial geometrical imperfection which is 10% of thickness. Each pit length and breadth are 80mm, and its depth is 5mm. 10mm is left between the plate boundary and pits and 20mm is left between two adjacent pits. The case ID means the

pits arrangement. For example, ‘all×2’ means the corroded area size in x and y direction is the whole plate length and 2 lines of pits along the plate breadth.

The calculation results of average stress-global strain relationship are shown in Fig. 3.25 and the obtained ultimate strength is shown in Table 3.8. It is concluded that, the size of corroded areas in length has very limited influence on residual ultimate strength. In another words, it is much more dominant of cross section area reduction rather than the overall plate material loss. For instance, compare the calculation results of Case (d) all×2 and Case (e) 2×all, the material loss of Case (d) is more than Case (e), the residual ultimate strength of Case (e) is much lower than Case (b). Therefore, it is more proper to apply the parameter of cross section area reduction to describe the residual ultimate strength of corroded plate.

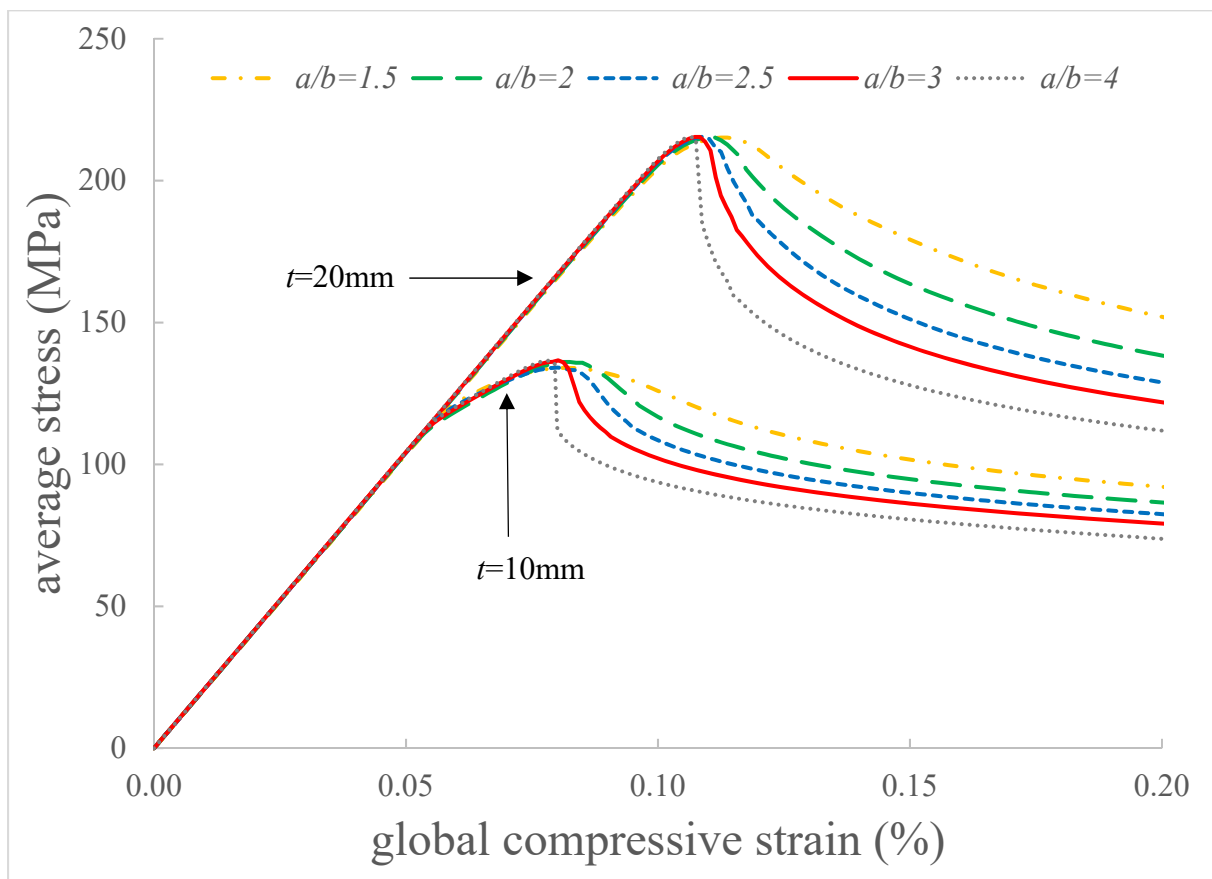


Fig. 3.22 Relationship between average stress and global strain of corroded plate (comparison between different α of plate, $w_0/t=0$)

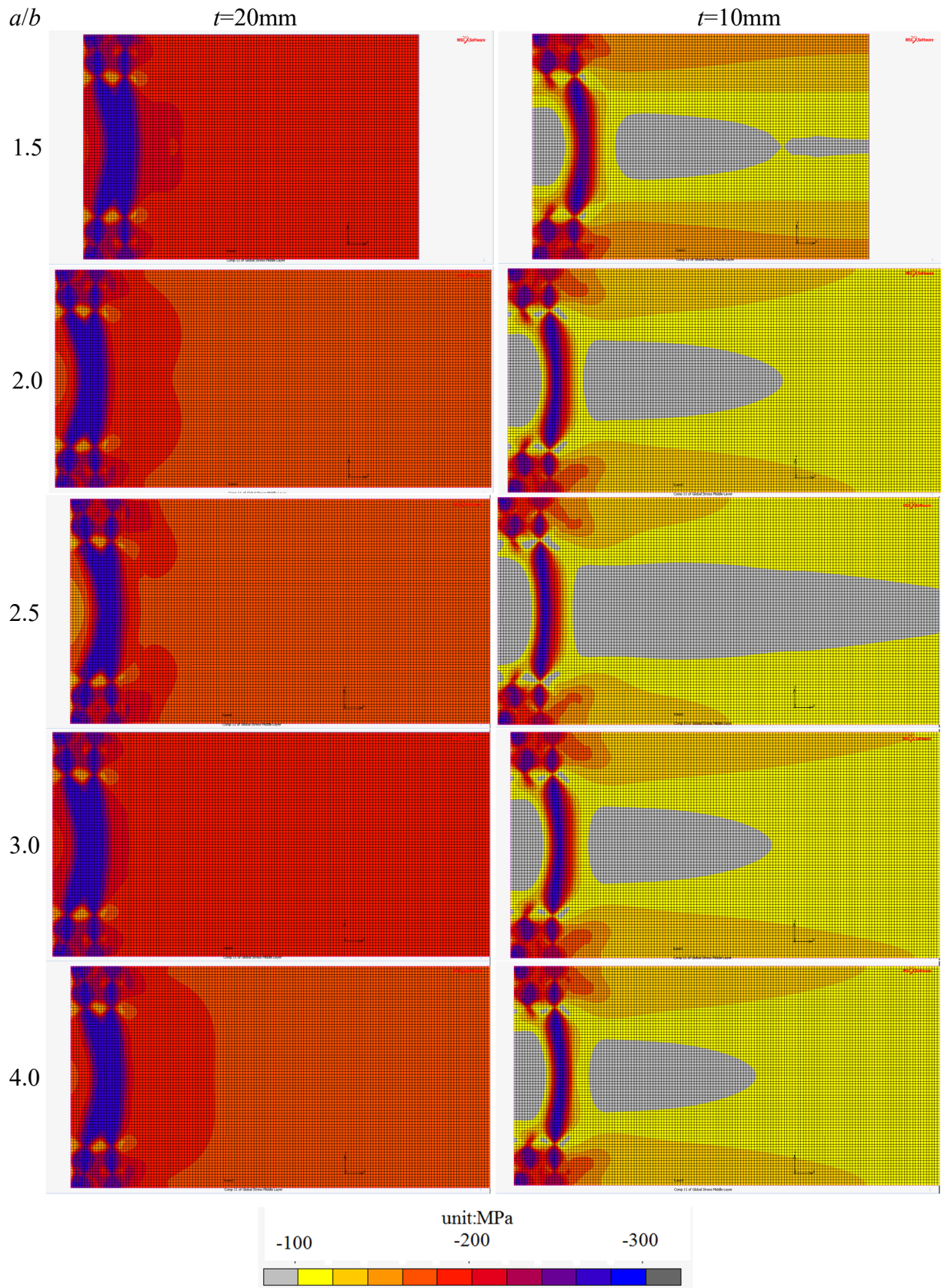


Fig. 3.23 σ_x distribution of the corroded area at ultimate state of plates with different a/b ratio ($t=20\text{mm}$ or 10mm , $w_0/t=0$)

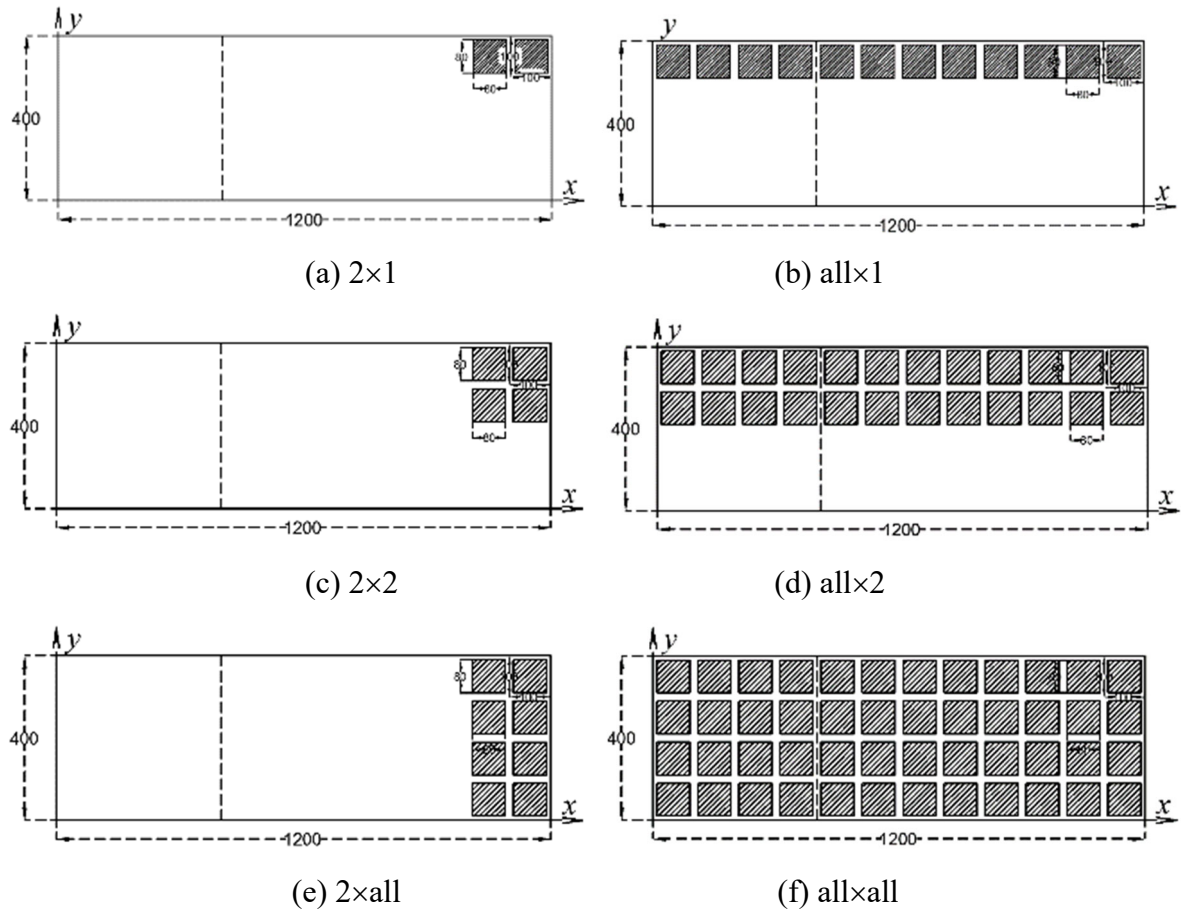


Fig. 3.24 Position of assumed corroded areas (different number of corroded area in length and breadth, $t=10\text{mm}$ or 20mm , $w_0/t=0.1$, $l=80\text{mm}$, $d=0.5t$)

Table 3.8 Results of ultimate strength (comparison of corroded plate with different number of corroded area in length and breadth, $w_0/t=0.1$)

Case No.	Ultimate strength(MPa)	
	$t=10\text{mm}$	$t=20\text{mm}$
intact	157.8	228.4
(a) 2×1	147.2	219.5
(b) $\text{all} \times 1$	143.6	212.6
(c) 2×2	135.0	201.4
(d) $\text{all} \times 2$	131.3	193.3
(e) $2 \times \text{all}$	118.9	165.3
(f) $\text{all} \times \text{all}$	118.4	165.3

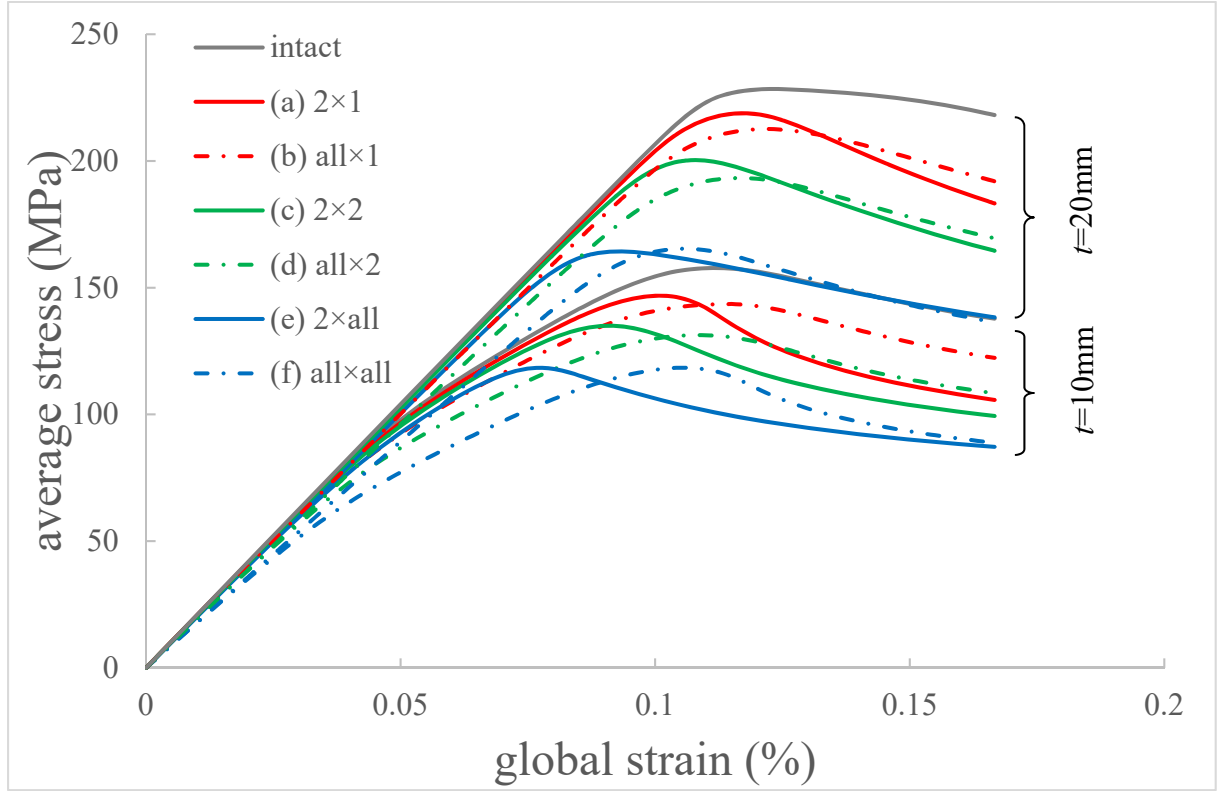


Fig. 3.25 Relationship between average stress and global strain of corroded plate (comparison between different numbers of corroded area sizes in plate length and breadth directions, $t=10$ mm or 20mm, $w_0/t=0.1$)

3.3.5 The effect of geometrical initial imperfection

In the research of residual ultimate strength of corroded plate, the geometrical initial imperfection is assumed to be $w_0/t=10\%$, for both thin (10mm) and thick (20mm) plate. However, it is needed to investigate the effect of geometrical initial imperfection.

In this section, the corroded plate size is 2400×800 mm. Pit corroded area locates in the corner part of the plate. The geometrical initial imperfection is the buckling mode. For $t=10$ mm, four values of w_0/t are selected, 40%, 20%, 10% and 1%. For $t=20$ mm, three values are selected, 10%, 5% and 1%. The case ID means the plate thickness and the ratio of initial imperfection amplitude to plate thickness. For example, in the Case ‘t10-10%’, the plate thickness is 10mm and the geometrical initial imperfection amplitude is 1mm ($=10 \times 10\%$). The residual ultimate strength calculation results are shown in Table 3.9.

Table 3.9 Residual ultimate stress comparison of corner corroded plate with different level of geometrical initial imperfection (plate size: 2400×800mm)

Case	$t10-40\%$	$t10-20\%$	$t10-10\%$	$t10-1\%$	$t20-10\%$	$t20-5\%$	$t20-1\%$
Intact plate, σ_{intact} (MPa)	150.21	155.00	157.77	160.20	228.43	233.65	235.14
Corroded plate, σ_u (MPa)	133.10	134.62	135.46	136.26	201.29	208.01	213.94
$\sigma_u/\sigma_{\text{intact}}$ (%)	88.61	86.85	85.86	85.06	88.12	89.03	90.98

cf.) 40%, 20%, 10% and 1% mean the imperfection amplitude (w_0) of plate divided by plate thickness (t)

The residual ultimate strength increases with the decrease of initial imperfection for both thick ($t=20\text{mm}$) and thin plate ($t=10\text{mm}$). Whereas, as the decrease of the w_0/t , the $\sigma_u/\sigma_{\text{intact}}$ increase for thick plate, but decrease for thin plate.

The reason is as follows. For thin plate, the ultimate state is global buckling. That means the deformation concentration occurs to the plate and deflection is the key factor. Both initial deflection and corroded pits contribute to the collapse caused by deflection. As w_0/t increases, the effect of initial deflection act on the collapse of the plate become more dominant. On the other hand, the influence of corrosion become more slightly. So w_0/t is larger, $\sigma_u/\sigma_{\text{intact}}$ is larger.

For thick plate, the ultimate state is local yielding that means the stress concentration occurs to the plate. If plate with initial deflection suffers from the same axial compressive force, the bending moment becomes larger as w_0/t increases. At the local yielding area, the axial compressive force and bending moment combined each other. So w_0/t is larger, $\sigma_u/\sigma_{\text{intact}}$ is smaller.

3.4 The dominant parameter to affect the residual ultimate strength of corroded plate

In order to investigate the effect of distribution of corroded area in breadth, the ultimate strength of plates with two kinds of distribution of corroded area is calculated. In Fig. 3.26, two cases (a) and (b) have the same cross section reduction. The pit size is 80mm, and plate is with 10% t initial deflection. In Case (a) 2×2 , $d=0.5t$, four pits are arranged on the plate two lines in x and y direction, pit depth is 50% of plate thickness. In (b) 2×4 , $d=0.25t$, eight pits are arranged on the plate two lines in x direction and four lines in y direction, pit depth is 25% of plate thickness. The residual ultimate strength calculation results of both $t=20\text{mm}$ and $t=10\text{mm}$ are shown in Fig. 3.27.

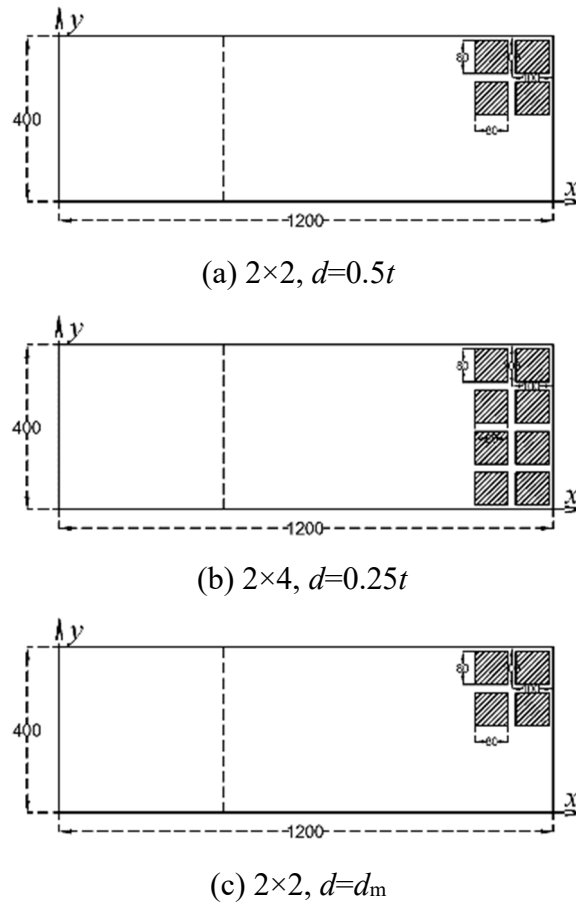


Fig. 3.26 Different corroded area size in plate breadth direction with the same cross section reduction ($l=80\text{mm}$, $w_0/t=0.1$)

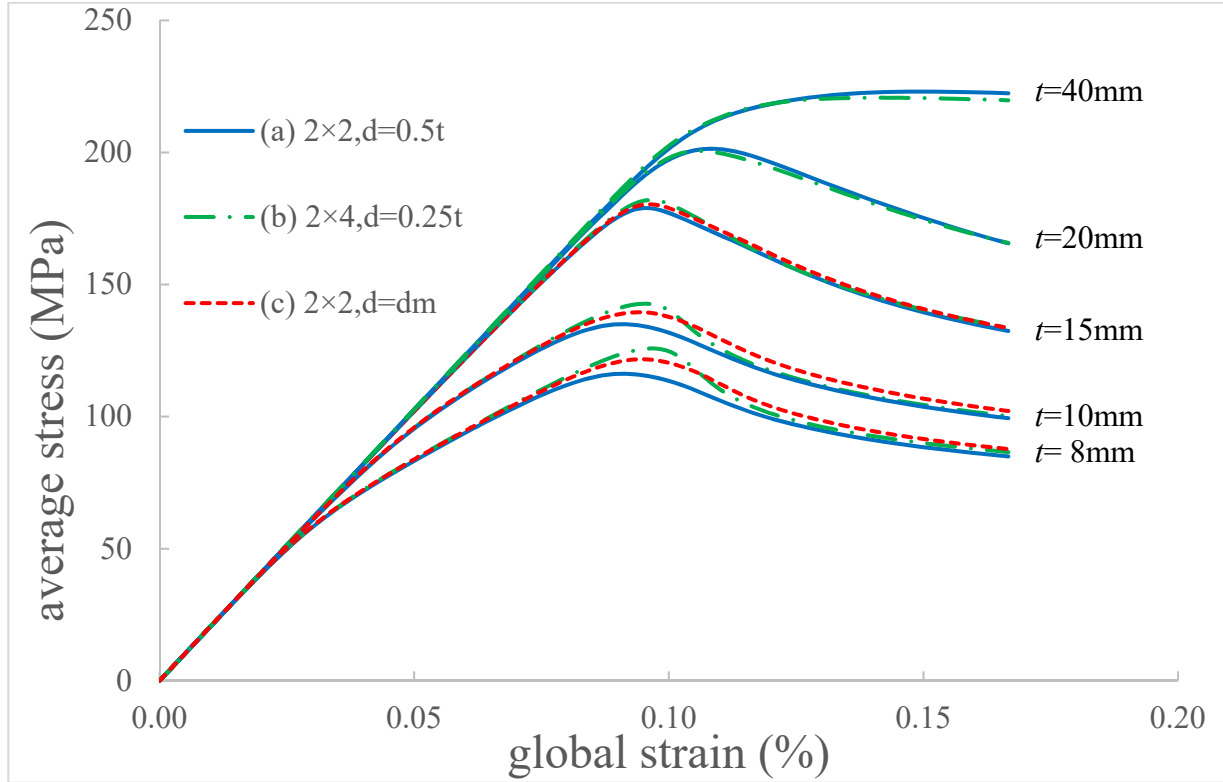


Fig. 3.27 Relationship between average stress and global strain of corroded plate (comparison between different corroded area with same cross section reduction, $w_0/t=0.1$)

For thick plate ($t=20\text{mm}$), with small β ($=1.34$), both cases give almost the same result. Meanwhile, for thin plate ($t=10\text{mm}$) with large β ($=2.68$), a little difference on the ultimate strength can be seen between different distribution of corroded area in breadth. The reason of this difference can be explained as follows, the corroded part near the boundaries in breadth affects more the bearing capacity under in-plane compression. That means, even if the overall cross section area reduction is same, the influence of edge corrosion on ultimate strength is more than that of central corrosion. Then Case (a) gives smaller ultimate strength than Case (b). Moreover, the calculation results of $t=8, 15$ and 40mm are also shown in Fig. 3.27.

In this paper, in order to take account of the different effect of edge corrosion and central corrosion on the ultimate strength, the concept of equivalent reduction of cross section is introduced as shown in Equation (3.6).

$$\frac{A_{r,eq}}{A_0} = \frac{A_r}{A_0} \left[\frac{b_e}{b} + K \cdot \left(1 - \frac{b_e}{b}\right) \right] \quad (3.6)$$

Where, b_e is the effective width, obtained from Equation (3.7);

A_0 is the area of original cross section;

A_r is the area of reduced cross section;

K can be regarded as the reduction of plate effective cross section area except effective width part, which equals to 0.5 in this research. The validity of the value of $K=0.5$ could be seen in Fig. 3.27.

$$\frac{b_e}{b} = \frac{\sigma_{\text{intact}}}{\sigma_y} \quad (3.7)$$

Where, b is the plate breadth;

σ_{intact} is the ultimate strength of intact plate.

In Fig. 3.26 Case (c), the plate size and geometrical initial imperfection and pit size are the same as Case (a) and (b). The pit arrangement of Case (c) is the same as Case (a), but the pit depth is d_m instead of half thickness in Case (a). The equivalent depth of pit corrosions, d_m , is determined as follows,

$$A_{r,eq} = 2 \times \frac{1}{2} l d_m \quad (3.8)$$

The value of d_m is derived from Equation (3.8). For example, the ultimate strength of intact plate ($t=10\text{mm}$, $w_0/t=0.1$) and yield strength are 157.8 MPa and 235MPa, respectively. Utilizing Equation (3.7), $b_e/b=0.67$ is derived. According to Equation (3.6), $A_{r,eq}/A_0$ becomes $0.835A_r/A_0$. Then d_m becomes 4.2mm by Equation (3.8).

As shown in Fig. 3.27, the result of modified model (c) is closed to that of model (b). From above, the concept of $A_{r,eq}$ is helpful for estimating of ultimate strength reduction of thin corroded plate with several corroded areas distributed in the breadth.

3.5 Simplified formula

The relationship between the ultimate strength reduction of corroded plate and the maximum reduction of cross section area is calculated in this section. The plate size is 2400×800mm and only a quarter of the whole plate is modelled. Three kinds of plate thickness are selected, 10mm, 15mm, and 20mm. The corroded areas arrangement is the same as show in Fig. 3.24 (a), (c) and (e). Pit size is 80mm×80mm. Pit depth is $0.5t$, $0.25t$ and $0.125t$. The calculation results of ultimate strength are shown in Table 3.10.

Table 3.10 Ultimate strength of corroded plate with different reduction of cross section area
($w_0/t=0.1$)

$a_x \times a_y - d$	Ultimate strength(MPa)		
	$t=20\text{mm}$	$t=15\text{mm}$	$t=10\text{mm}$
intact	228.4	204.7	157.8
$2 \times 1 - 0.5t$	219.5	194.0	147.2
$2 \times 1 - 0.25t$	225.6	201.0	155.1
$2 \times 1 - 0.125t$	227.4	203.5	157.0
$2 \times 2 - 0.5t$	201.4	179.0	135.0
$2 \times 2 - 0.25t$	219.6	195.0	150.0
$2 \times 2 - 0.125t$	226.1	201.8	155.9
$2 \times \text{all} - 0.5t$	165.3	149.6	118.9
$2 \times \text{all} - 0.25t$	201.2	182.0	143.0
$2 \times \text{all} - 0.125t$	220.9	198.4	154.3

For cases of pits with $t=10\text{mm}$ and 15mm , the effective width effect has an influence on the residual ultimate strength of corroded plate. So, based on Equation (3.7), the equivalent cross section reduction, $A_{r,eq}$ could be modified in Table 3.11.

According to the calculation results in Table 3.10 and Table 3.11, the relationship between the reduction of ultimate strength of corroded plate and the equivalent reduction of cross section could be expressed as,

$$\frac{\sigma_u}{\sigma_{\text{intact}}} = 1 - 2.5 \times \sqrt[4]{\beta \left(\frac{A_{r,eq}}{A_0} \right)^{1.43}} \quad (3.9)$$

Where, σ_u is the ultimate strength of corroded plate;

σ_{intact} is the ultimate strength of intact plate with initial geometrical imperfection;

β is the plate slender ratio;

$A_{r,eq}$ is the area of equivalent reduced cross section;

A_0 is the area of initial cross section.

Table 3.11 Equivalent reduction of cross section ($t=10\text{mm}$ and 15mm)

$t-a_x \times a_y - d$	A_r/A_0 (%)	$A_{r,eq}/A_0$ (%)
15-2×all -0.5 t	20	18.7
15-2×all -0.25 t	10	9.35
15-2×all -0.0125 t	5	4.675
10-2×all -0.5 t	20	16.7
10-2×all -0.25 t	10	8.35
10-2×all -0.125 t	5	4.175

The comparison of Equation (3.9) and calculation results is shown in Fig. 3.28. An acceptable agreement of both is obtained.

However, in most real cases, the size (length and breadth) of corrosion area is easy to be measured rather than depth. Although the ratio of pit depth to pit diameter is 1:4~1:10, if the pits overlaps each other, it is also difficult to estimate the pit depth. So it is needed to measure and estimate several potential positions where might be the maximum pit depth such as the center part of the largest corroded area. The most possible situation is that the corroded area extends the same in all directions. So the deepest position is the center of each pit corrosion area in which position the plate might first be corroded. And then, after obtaining the estimated pit depth, the equivalent pit depth could be calculated by utilizing Equation (3.6) with taking the plate slender ratio into account. And also, substituting the equivalent reduction of cross section area into Equation (3.9), the residual ultimate strength could be estimated.

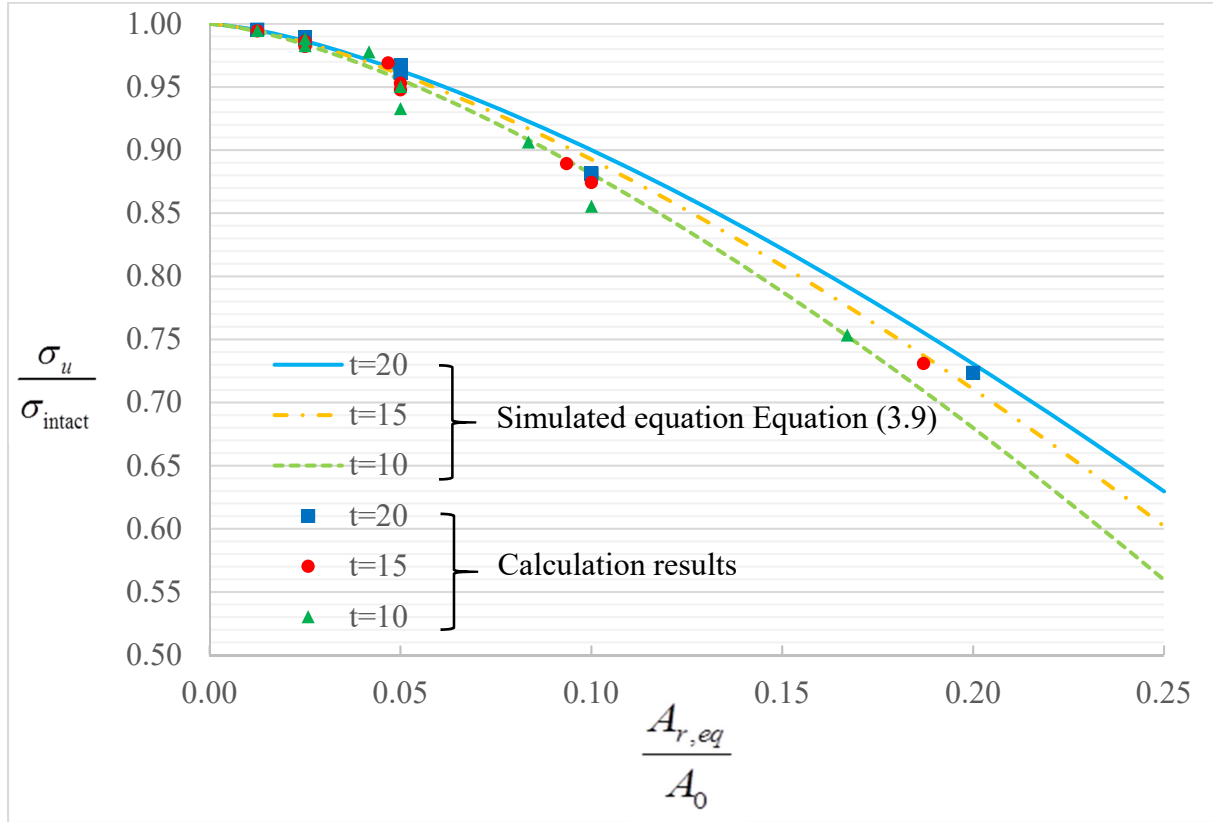


Fig. 3.28 Comparison of calculation results and simulated equation

3.6 Conclusions

By the application of nonlinear FE software MSC.Marc, an efficient method is proposed to model pit corroded plate by large size of shell elements. The validity of this method is confirmed by comparing the calculation results obtained by solid elements model and proposed shell elements model.

With the help of the proposed method, a series of calculations are performed for investigating the residual ultimate strength of corroded plate under compression, and the following conclusions are derived.

First, the most severe corroded position for ultimate strength reduction is the corner part of the plate.

Second, the reduction of cross section area has dominant influence on the residual ultimate strength of pit corroded plate.

Third, if more than one area in length are corroded, the residual ultimate strength is the same as that of the plate with the most severe corroded area only.

Forth, the effects, such as pit shape, the corroded area size and the ratio of plate length to breadth, have almost no influence on the residual ultimate strength of pit corroded plate.

Then, in order to take account of the different effect of edge corrosion and central corrosion on the ultimate strength, the concept of equivalent reduction of cross section, $A_{r,eq}$, is introduced. There is a little difference on the ultimate strength of different distribution of corroded area in breadth between thick and thin plate. Therefore, this parameter is determined to unify the reduction of cross section both of thick and thin plate.

Final, a non-dimensional simplified formula is derived to represent the relationship between the residual ultimate strength and the equivalent reduction of cross section area.

Chapter 4. Residual Ultimate Strength of Pit Corroded Tubes

4.1 Introduction

In this chapter the residual ultimate strength of pit corroded tube members is investigated. The past existing study on the strength of a corroded tube member is less than that of a corroded plate. For example, Yamane et al ^[59] investigated the collapse behavior of corroded tubes under bending and compressive loading, however, the general corrosion was considered in their study. The investigation of the effect of pit-corrosion on the collapse behavior of tube members is limited.

In this chapter, first, the effect of corroded area position in tube axial direction is investigated. Second, the effect of corroded area size in tube axial direction is studied. Third, the relationship between residual ultimate strength and the cross section area reduction. The area reduction contains two independent parameters, those are, area size and depth. They are investigated separately here. Then, the effect of tube scantling on the residual ultimate strength is worked out. Final, the coupling effect of initial geometrical imperfection is investigated.

The pit corroded part could be modelled by large size of shell elements by applying the modelling method in Chapter 3. The calculation results are accurate with an efficient procedure. So in this part, using the same modelling method the residual ultimate strength of pit corroded tube members is investigated.

In Section 4.2, the basic case is illustrated which is the same as the Basic case in collision effect in Chapter 2. The tube scantlings and material properties are shown. Also the tube boundary condition and FEM model mesh division is explained. The size of one pit and pit corroded area size is stated then. In Section 4.3, the influence of the effects of pit area position, pit area size in tube axial, pit area size in tube circumferential direction and pit depth is studied separately, for the Basic case. And two parameters are believed to be dominant to influence the residual

ultimate strength of corroded tube members, they are the pit area size in tube circumferential direction and the pit depth. Based on the residual ultimate strength numerical calculation results, a simplified formula is derived to show the relationship between the residual ultimate strength and the two selected dominant parameters. Next, the simplified formula is modified by taking into consideration of the effect of tube scantlings in Section 4.5. In Section 4.6, the coupling effect of tube geometrical initial imperfection is investigated. In Section 4.7, the effect of the variation of tube scantlings and material properties due to manufacturing error is studied. Final, remarkable conclusions are obtained in Section 4.8.

4.2 Basic case

4.2.1 Tube scantling and material property

The Basic case is the selected the same as it in Chapter 2. The tube scantling and material property are as follows,

Tube length,	$L=30\text{m};$
Tube diameter,	$D=2.5\text{m};$
Tube thickness,	$t=40\text{mm};$
Yield stress,	$\sigma_y=235\text{MPa};$
Young's modulus,	$E=2.1\times 10^5\text{MPa}.$

4.2.2 Boundary condition

Boundary condition is simply supported on both ends, as shown in Fig. 4.1. All the nodes in the end circle is connected with the center by RBE2 links ^[65] in both ends. Only the centers of both end sections are restricted. The displacement in x and y directions is fixed and the rotation around z axis is also fixed, $u_x = u_y = \theta_z = 0$.

Loading condition is enforce displacement in the center of one end ($z=L$), the other end ($z=0$) the center is fixed in z direction.

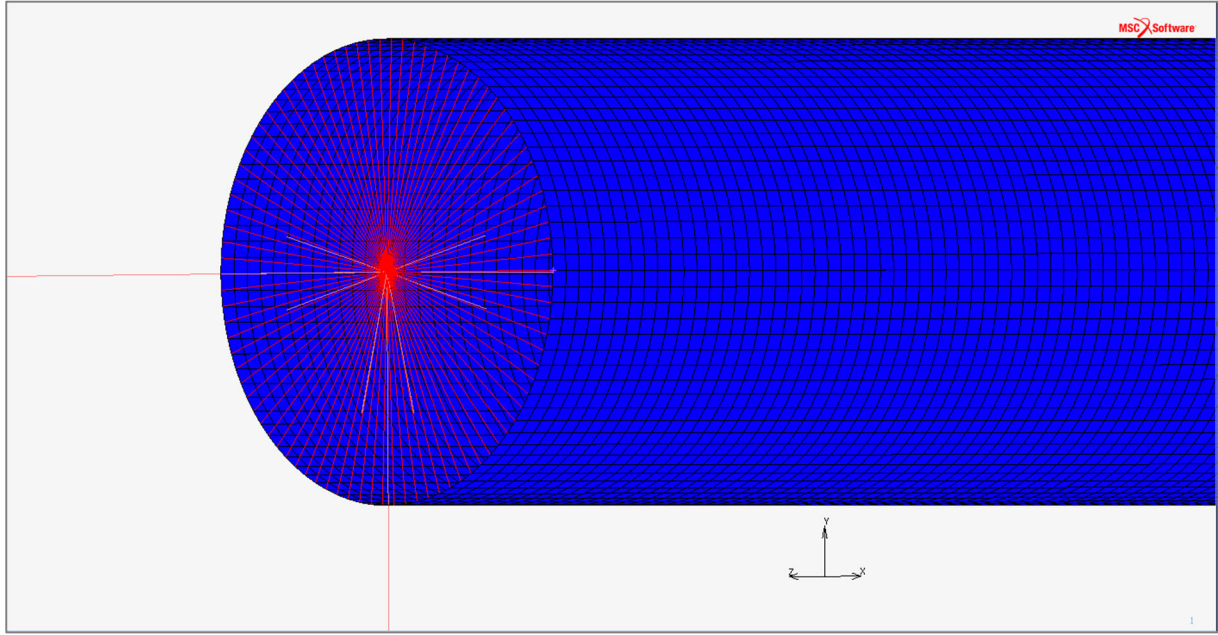


Fig. 4.1 Simply supported boundary condition

4.2.3 Mesh division

When almost square elements are used, the mesh size of 4 degrees in circumferential direction will give adequate accurate results. It was confirmed by changing the size of element from 1° , 2° , 3° , 4° , 5° , 8° , 10° and 15° . The calculation results will be shown later in Section 4.9 Appendix.

So for $D=2.5\text{m}$, the element size is $87.3 \times 100\text{mm}$. The element number in tube length and circumferential direction is 300 and 90, respectively.

4.2.4 Pit area size and position

As it is confirmed in the previous research, 4 mesh is needed in half of one pit to provide accurate result. So the pit size is $700 \times 800\text{mm}$, pit depth is 20mm ($0.5t$). The assumed pit shape is rectangular. The size and position of corroded area is shown in Fig. 4.2. Three parameters are selected to describe the characters of pit. Those are the longitudinal length of corroded area, l_c , the center angle of corroded area, α , and the depth of pits, d . Only the position in tube axial direction, z_c , is selected as calculation parameter to describe the location of the corroded area, since the tube is symmetrical in the circumferential direction.

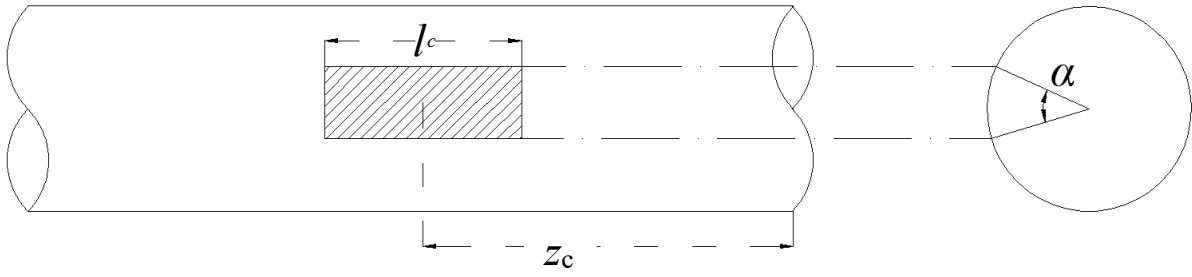


Fig. 4.2 Corroded area size and position

4.3 The effects of pit corrosion factors

In Chapter 3, in the research of residual ultimate strength of pit corroded plate, the dominant parameter is the (equivalent) cross section area reduction. It has similar situation in the research of residual ultimate strength of pit corroded tubes. So in this section, the relationship between the residual ultimate strength of corroded tube and the cross section area reduction. At first the effect of corroded area position in the tube axial direction is carried out. Then the effect of pit area size is investigated. Third the effect of cross section reduction is studied.

4.3.1 Ultimate strength of intact tubes

First, the ultimate strength of intact tube without geometrical initial imperfection and corrosion is estimated. The details of those calculation will be shown later in appendix. Based on those calculation results, the ultimate strength of intact tubes is the same as tube material yield stress, 235MPa.

4.3.2 The effect of corroded area position

The effect of corroded area position in axial direction of tube is investigated. The pit arrangement is the same as the Fig. 4.3 (3×3). 3 cases with different positions, $z_c=15000\text{mm}$ ($1/2L$), $z_c=7500\text{mm}$ ($1/4L$) and $z_c=3000\text{mm}$ ($1/10L$) are investigated. The meaning of (3×3) will be explained later in Section 4.3.3. The calculation results of residual ultimate strength are shown in Table 4.1. The effect of corroded area position in axial direction has limited effect on the residual ultimate strength. Also, the most severe case is that the corrode area is located in the middle span of the tube. And in the following cases, the corroded area located in the middle span of the tube.

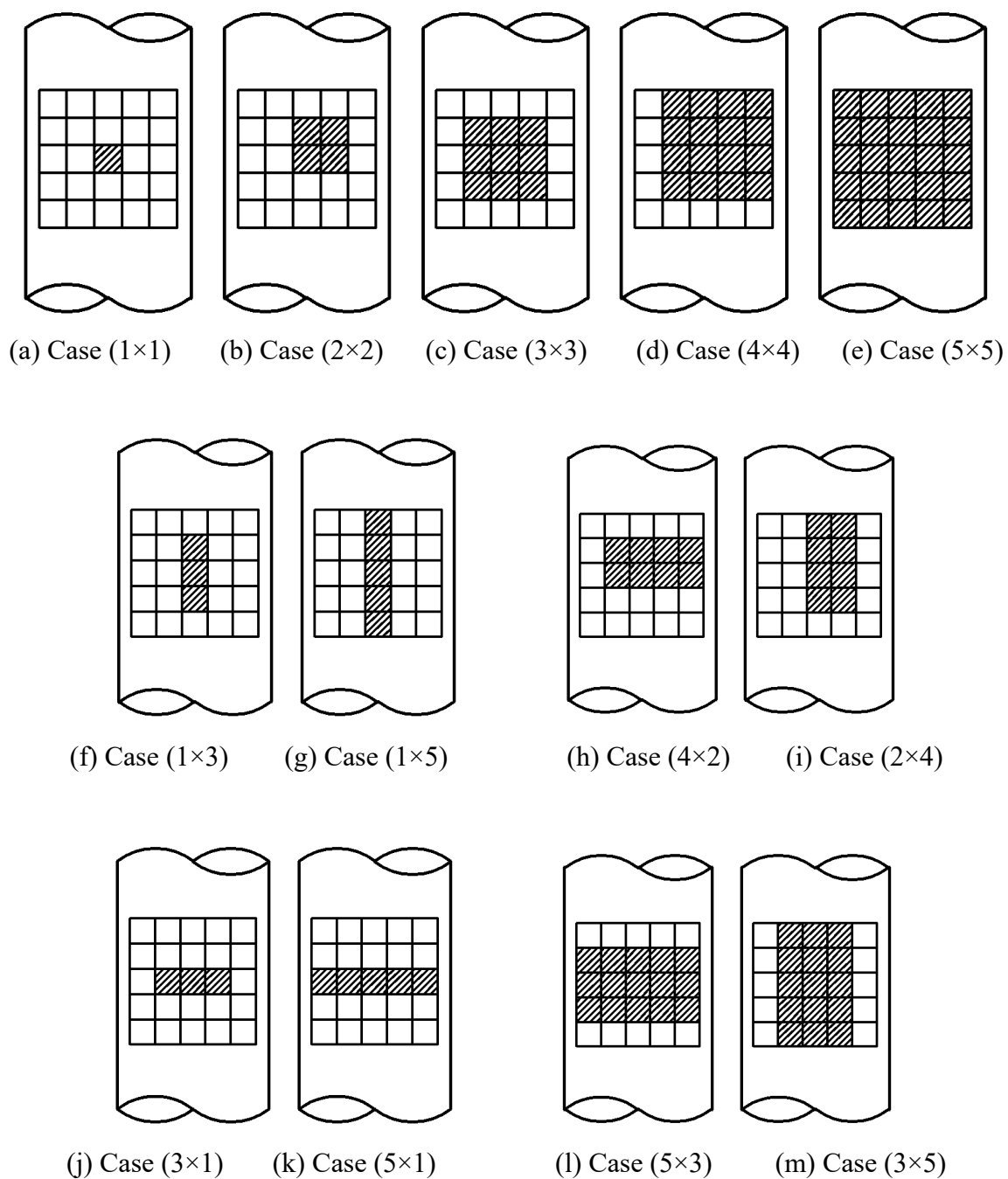


Fig. 4.3 Pit arrangement (the shadow parts are pit corroded, the blank parts are intact)

Table 4.1 Ultimate strength calculation results of tubes with different corroded area position in axial direction

Case	F (MN)	σ (MPa)
$z_c=1/2L$	63.89	203.37
$z_c=1/4L$	64.01	203.75
$z_c=1/10L$	64.91	206.61

4.3.3 The effect of pit area size

The effect of corroded area size in tube axial direction is studied. The position of corroded part is the middle span of the tube length. Generally, the pit size is the same in all directions. So at first, pit arrangement as (1×1) , (2×2) , (3×3) , (4×4) and (5×5) of Fig. 4.3 are compared with each other. The case is named by the pit number in circumferential direction $\times$ pit number in axial direction, $(n_\theta \times n_z)$. And the shadow parts are pits, blank means intact tube.

Table 4.2 shows the calculation results of residual ultimate strength with different sizes of corroded area. Larger corroded area leads to smaller residual ultimate strength. In order to investigate which parameter is dominant in the influence on the residual ultimate strength, l_c or α , all the other pit arrangement methods are calculated to obtain the results of ultimate strength.

From the results shown in Table 4.2, the effect of corroded area size in axial direction is limited. So the maximum cross section reduction has more dominant influence on the influence on the residual ultimate strength, which is the same conclusion as that in corroded flat plate.

4.3.4 The effect of cross section reduction

As it is illustrated above, the cross section reduction affects the residual ultimate strength much. The cross section reduction is combined by two parameters, the corroded area size in tube circumferential direction and the pit depth. In this section, these two parameters are investigated separately. The maximum cross section is calculated as,

$$A_r = \frac{1}{2}(\alpha R)d \quad (4.1)$$

So the cross section area reduction ratio is,

$$\frac{A_r}{A_0} = \frac{0.5(\alpha R)d}{2\pi R \cdot t} = 0.5 \frac{\alpha}{2\pi} \frac{d}{t} \quad (4.2)$$

Where, α is the center angle of corroded area shown in Fig. 4.2 and d is pit depth.

Table 4.2 Ultimate strength calculation results of tubes with different corroded area sizes

Case	Ultimate strength, σ_u (MPa)
1×1	223.11
1×3	222.31
1×5	222.14
2×2	212.53
2×4	212.00
3×1	202.83
3×3	203.37
4×2	196.47
4×4	196.02
5×1	191.35
5×3	191.08
5×5	190.53

Then the effect of tube cross section reduction is investigated. The pit arrangement is as (1×3), (3×3) and (5×3) in Fig. 4.3. An additional case is that the pit depth is 6.68mm (0.167*t*) and 33.33mm (0.833*t*) with the pit arrangement as (3×3) is performed. The case ID shows the pits arrangement and the pit depth.

The residual ultimate strength calculation results are shown in Table 4.3. And the corroded depth is also an important parameter. It means the concentration of material loss has much influence on the residual ultimate strength.

Table 4.3 Ultimate strength calculation results of tubes with different cross section reduction

Case	A_T/A_0 (%)	Ultimate strength, σ_u (MPa)
$3 \times 3 \ 0.167t$	4.45	225.71
$3 \times 3 \ 0.833t$	22.22	175.87
$1 \times 3 \ 0.5t$	4.45	222.31
$3 \times 3 \ 0.5t$	13.33	203.37
$5 \times 3 \ 0.5t$	22.22	191.08

4.4 Coupling effect of geometrical initial imperfection

The effect of geometrical initial imperfection is investigated in this section. Three kinds of geometrical initial imperfection are considered. The tube is the same as the Basic case. Pits arrangement is (3×3) with the pit depth of $0.5t$. The introduction of the geometrical imperfection is realized by offset the nodes in the tube radius direction. In the corroded area, the node offset direction due to imperfection and corrosion is the same.

One is the column buckling shape with one half wave,

$$w_z = w_{0z} \sin\left(\frac{\pi z}{L}\right) \quad (4.3)$$

Another is elastic diamond buckling shape with three waves in circumferential direction,

$$w_\theta = w_{0\theta} \cos(3\theta) \sin\left(2\pi \frac{mz}{L}\right) \quad (4.4)$$

The last is the uniform circumferential inward imperfection,

$$w_r = w_{0r} \sin\left(n \frac{\pi z}{L}\right) \quad (4.5)$$

The residual ultimate strength calculation results of corroded tube with geometrical initial imperfection calculation results are shown in Table 4.4, Table 4.5 and Table 4.6, respectively.

Table 4.4 Residual ultimate strength of corroded tube with column buckling initial imperfection

w_{0z}/L	σ_u (MPa)	σ_0 (MPa)	σ_u/σ_0
0	203.37	235.00	0.865
0.01	147.15	170.45	0.863
0.001	195.95	226.54	0.865
0.0001	202.6	234.21	0.865

Table 4.5 Residual ultimate strength of corroded tube with diamond buckling initial imperfection

$w_{0\theta}/t$	σ_u (MPa)	σ_0 (MPa)	σ_u/σ_0
0	203.37	235.00	0.865
0.001	203.34	234.37	0.868
0.01	203.27	234.40	0.867
0.1	201.94	232.65	0.868
0.5	191.08	222.69	0.858

Table 4.6 Residual ultimate strength of corroded tube with uniform circumferential initial imperfection

$n-w_{0r}/t$	σ_u (MPa)	σ_0 (MPa)	σ_u/σ_0
1-0.2	202.07	233.60	0.865
1-1	196.88	227.70	0.865
3-0.2	202.26	233.73	0.865
3-1	197.76	228.16	0.867
5-0.2	202.56	233.96	0.866
5-1	199.14	229.18	0.869

From the results, the following conclusion could be derived,

$$\left(\frac{\sigma_u}{\sigma_0} \right)_{\frac{w_{0z}}{L}, \frac{w_{0\theta}}{t}, \frac{w_{0r}}{t}} = \left(\frac{\sigma_u}{\sigma_0} \right)_{\text{intact}}$$

Where, σ_u is the residual ultimate strength of corroded tube;

σ_0 is the residual ultimate strength of intact tube without corrosion.

So no coupling effects are exist in the residual ultimate strength of corroded tubes between geometrical initial imperfection and corrosion effect. The corrosion effect tubes with and without geometrical initial imperfection is in the same way.

4.5 Simplified formula

In order to shown the relationship between the residual ultimate stress and the corrosion situation of the pit corroded tube members, a simplified formula is required to be proposed. In the above sections the effects of size of corroded parts in axial and circumferential direction of the tube and the pit depth have been investigated. And the parameters of center angle of corroded area, α , and pit depth, d , are selected to be the dominant factors to describe the corrosion situation.

So in this section, according to the results in the above sections, the effect of corrosion depth should be treated individually. As a result, the following cases are calculated, $d=0.1t$, $0.25t$ and $0.75t$. And the calculation results of residual ultimate strength of additional cases is shown in Table 4.7.

Table 4.7 Ultimate strength calculation results of tubes with different pit depth of additional cases

Case	Ultimate strength, σ_u (MPa)
3×3 0.1t	229.95
3×3 0.25t	220.40
3×3 0.75t	183.16

Together with all the residual ultimate strength calculation results in Table 4.2 and Table 4.3, the following formula is proposed to describe the residual ultimate strength of pit corroded tubes,

$$\frac{\sigma_u}{\sigma_0} = 1 - 0.86 \cdot \eta = 1 - 0.86 \left(\frac{\alpha}{2\pi} \right)^{0.75} \left(\frac{d}{t} \right)^{1.2} \quad (4.6)$$

Where, α is the center angle of corroded area;

d is the pit depth;

The range of t is from 20mm to 60mm, the range of d is from 0 to half of t .

The comparison results of residual ultimate strength obtained from the above formula and calculation results are shown in Fig. 4.4. Good agreement is achieved, so the derived simplified Equation (4.3) is accurate to shown the relationship between the residual ultimate stress and the corrosion situation of the pit corroded tube members.

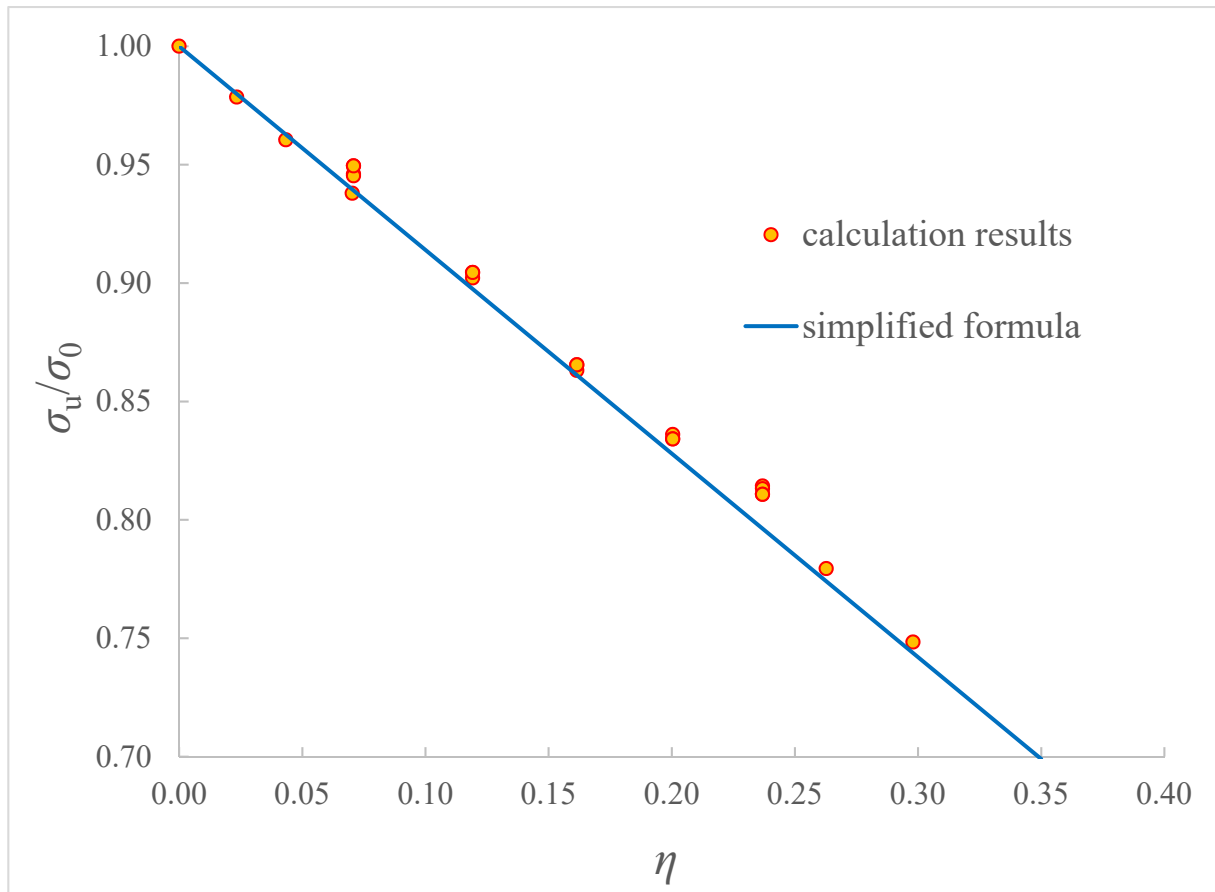


Fig. 4.4 Comparison of simplified formula and calculation results

4.6 Modification factor due to tube scantlings

The relationship between the residual ultimate strength of pit corroded tube and the corrosion situation is illustrated in Section 4.5. However, the tube scantlings are the same in the above study. In order to clarify the effect of tube scantlings, the residual ultimate strength of tube members with different length, diameter and thickness is investigated in this section. In the calculation cases, to control the variable, the pits arrangement is (3×3) and pit depth is half of the shell thickness, $d=0.5t$.

As it has been illustrated in Chapter 2, the ranges of the tube scantlings are as follows,

L : 15~45m; D : 1.8~4.0m; t : 20~60mm.

The sensitivity of L/D and D/t is investigated in this section. As shown in Table 4.8, the maximum and minimum values of each above parameters are selected to model and then calculated.

Table 4.8 Residual ultimate strength calculation result of tubes with different scantlings.

Case	L (m)	D (m)	t (m)	L/D	D/t	σ_u	σ_0	σ_u/σ_0
Basic	30	2.5	0.04	12	62.5	203.37	234.4	0.8676
L15	15	2.5	0.04	6	62.5	206.46	234.34	0.8810
L45	45	2.5	0.04	18	62.5	200.31	234.55	0.8540
D1.8	30	1.8	0.04	16.67	45	202.37	234.71	0.8622
D4.0	30	4	0.04	7.5	100	200.34	233.56	0.8578
T20	30	2.5	0.02	12	125	193.47	233.51	0.8285
T60	30	2.5	0.06	12	41.67	204.46	234.7	0.8712

The relationship between σ_u/σ_0 and L/D is linear as shown in Table 4.8. However, for D/t , the relationship is more complicated. It means the ratio of σ_u/σ_0 is more sensitive with shell thickness. So by changing the shell thickness, calculation cases is performed as shown in Table 4.9. In these cases, the tube length is 30m and diameter is 2.5m.

Table 4.9 Residual ultimate strength calculation result of tubes with different shell thicknesses
($L=30\text{m}$, $D=2.5\text{m}$)

t (mm)	D/t	σ_u	σ_0	σ_u/σ_0
20	125	193.47	233.51	0.8285
25	100	198.42	233.9	0.8483
30	83.33	200.91	234.11	0.8582
35	71.43	202.48	234.3	0.8642
40	62.5	203.37	234.4	0.8676
45	55.56	203.89	234.5	0.8695
50	50	204.18	234.6	0.8703
55	45.45	204.34	234.6	0.8710
60	41.67	204.46	234.7	0.8712

Although, the variation of σ_u/σ_0 is in a relatively small range, the influence of tube scantlings should also be taken into account. Combing the residual ultimate strength calculation results shown in Table 4.8 and Table 4.9, the relationship between σ_u/σ_0 and the tube scantlings could be derived as follows,

$$\left(\frac{\sigma_u}{\sigma_0}\right)_{3 \times 3} = f\left(\frac{L}{D}, \frac{D}{t}\right) = 0.895 - 2.64 \times 10^{-7} \left(\frac{L}{D}\right) \left[10000 - 127 \left(\frac{D}{t}\right) + 1.73 \left(\frac{D}{t}\right)^2\right] \quad (4.7)$$

The comparison of the above equation and calculation results are shown in Fig. 4.5. And when $L/D=12$, $D/t=62.5$, $f\left(\frac{L}{D}, \frac{D}{t}\right)=0.86$. So the residual ultimate strength of pit corroded tube could be estimated by the following equation,

$$\frac{\sigma_u}{\sigma_0} = 1 - f\left(\frac{L}{D}, \frac{D}{t}\right) \cdot \eta \quad (4.8)$$

$$\text{Where } \eta = \left(\frac{\alpha}{2\pi}\right)^{0.75} \left(\frac{d}{t}\right)^{1.2};$$

$$f\left(\frac{L}{D}, \frac{D}{t}\right) = 0.895 - 2.64 \times 10^{-7} \left(\frac{L}{D}\right) \left[10000 - 127 \left(\frac{D}{t}\right) + 1.73 \left(\frac{D}{t}\right)^2 \right];$$

The range of L is from 15m to 45m. The range of D is from 1.5m to 4.0m. The range of t is from 20mm to 60mm.

Equation (4.8) is the modified simplified formula of Equation (4.6) with consideration of the effect of tube scantlings. In Equation (4.8), the residual ultimate strength of pit corroded tube is shown to be slightly influenced by the tube scantlings. The cross section area reduction is still the dominant parameter. Although point A in Fig. 4.5 seems far away from the solid line, the range is from 0.81 to 0.89. So the different of point A and solid line is still within 5%.

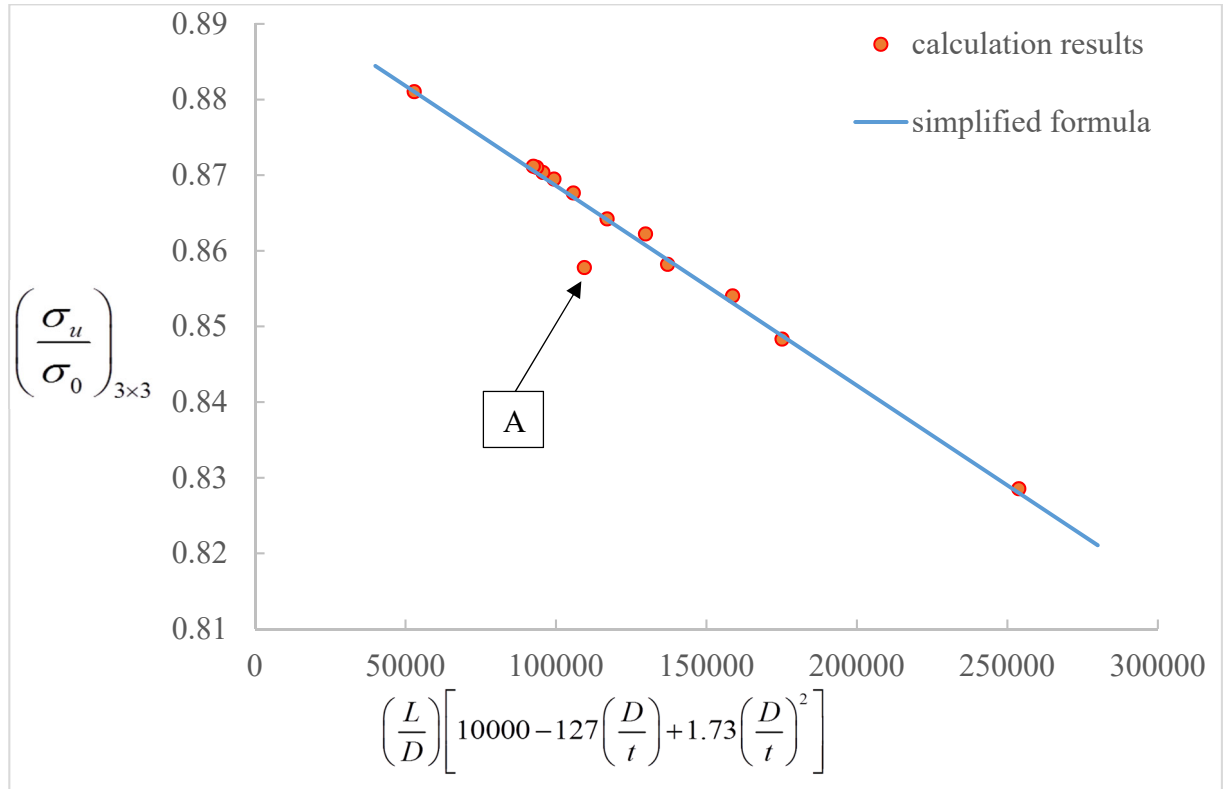


Fig. 4.5 The comparison of calculation results and simulation equation

4.7 Applicability of proposed formula

As illustrated in Section 2.6, the variation of tube shell thickness and material physical properties could also have influence on the simplified equation. That equation which proposed in Section 3.9 shows the relationship between the residual ultimate strength of pit corroded tube

and the tube scantlings and pit properties. In this section, the effect of shell thickness variation is investigated first. Then, the effect of material properties, Young's modulus, E , and yield stress, σ_y , are studied.

4.7.1 The effect of tube shell thickness

The effect of tube shell thickness is investigated by changing the initial thickness value of the Basic case in Section 3.2. The tube scantlings and physical properties are,

$$L=30\text{m}, \quad D=2.5\text{m}, \quad t=40\text{mm}, \quad \sigma_y=235\text{MPa}, \quad E=2.1 \times 10^5 \text{MPa}.$$

The pit depth, d , is 20mm. And the corrosion pit arrangement is (3×3) type. Two additional thickness value is selected, 42 and 44mm, the same as those in Section 2.6. The other model parameters are the same as those in Basic case. The comparison of residual ultimate strength from numerical simulations is shown in Table 4.10. The difference between the results from the simulated formula and numerical calculation is very limited. The reason is that, the effect of tube scantlings, especially thickness, has already taken into consideration in the derivation procedure of the simulated formula. This reason is the same that the effect of tube scantling also has no influence on the residual ultimate strength of collided tube in Section 2.6. And the influence of effect of variation range of tube length and diameter is also limited in the same way as the thickness.

Table 4.10 Comparison of calculation results with different values of shell thickness

Thickness, t (mm)	σ_u (MPa)	Calculated σ_u/σ_0	Simulated σ_u/σ_0	Error (%)
40	203.37	0.8654	0.8600	-0.63
42	205.31	0.8736	0.8678	-0.67
44	206.99	0.8808	0.8749	-0.68

cf.) Error = (Simulated - Calculated) / Calculated $\times 100\%$

4.7.2 The effect of material Young's modulus

In the research of residual ultimate strength of corroded tubes, the calculation is a static analysis. No strain rate and strain hardening effects are introduced into the numerical models. The

calculation results are dependent on the material physical properties. As the mild steel is applied in the analysis, the Young's modulus, E and yield stress, σ_y is fixed to be $2.1 \times 10^5 \text{MPa}$ and 235MPa , respectively.

The effect of Young's modulus, E , is investigated. Two additional values are selected, $E_1 = 2.3 \times 10^5 \text{MPa}$ and $E_2 = 2.5 \times 10^5 \text{MPa}$, according to Gaspar et al ^[34]. The calculation results shown in Table 4.11. According to these comparison results, the effect of E has almost no influence on the residual ultimate strength of corroded tubes. And the simulated formula is stable, in spite of the variation of Young's modulus.

Table 4.11 Comparison of calculation results with different values of Young's modulus

Young's modulus, E (MPa)	σ_u (MPa)	Calculated σ_u/σ_0	Simulated σ_u/σ_0	Error (%)
$E = 2.1 \times 10^5$	203.37	0.8654	0.8600	-0.63
$E_1 = 2.3 \times 10^5$	203.86	0.8675	0.8600	-0.87
$E_2 = 2.5 \times 10^5$	204.28	0.8693	0.8600	-1.07

cf.) Error = (Simulated - Calculated) / Calculated $\times 100\%$

4.7.3 The effect of material yield stress

And then the effect of material yield stress, σ_y , is worked out. As it is illustrated in Section 4.1, and the same values are selected as those in Section 4.2, three additional values are selected,

$\sigma_{y1} = 255 \text{MPa}$, $\sigma_{y2} = 269 \text{MPa}$, $\sigma_{y3} = 300 \text{MPa}$.

The comparison results of residual ultimate strength are shown in Table 4.12. The relationship between residual ultimate strength ratio of corroded tubes to intact ones and tube material yield stress is shown in Fig. 4.6. Although, in Fig. 4.6, almost linear relationship is presented, the range of σ_u/σ_y is still varies in a limited extent. So that, the effect of material yield stress could be neglected. So the proposed equation in Chapter 3 which aims at the residual ultimate strength of corroded tubes is considerably steady. The application of steel with higher value of yield stress will not donate to increase the ultimate strength of corroded tubes. On the contrast, this measure will decline that. The reason is that higher value of yield stress leads to more remarkable stress concentration compared to lower values.

Table 4.12 Comparison of calculation results with different values of yield stress

Yield stress, σ_y (MPa)	σ_u (MPa)	Calculated σ_u/σ_0	Simulated σ_u/σ_0	Error (%)
$\sigma_y=235$	203.37	0.8654	0.8600	-0.63
$\sigma_{y1}=255$	220.14	0.8633	0.8600	-0.39
$\sigma_{y2}=269$	231.86	0.8619	0.8600	-0.23
$\sigma_{y3}=300$	257.64	0.8588	0.8600	0.13

cf.) Error = (Simulated - Calculated) / Calculated $\times 100\%$

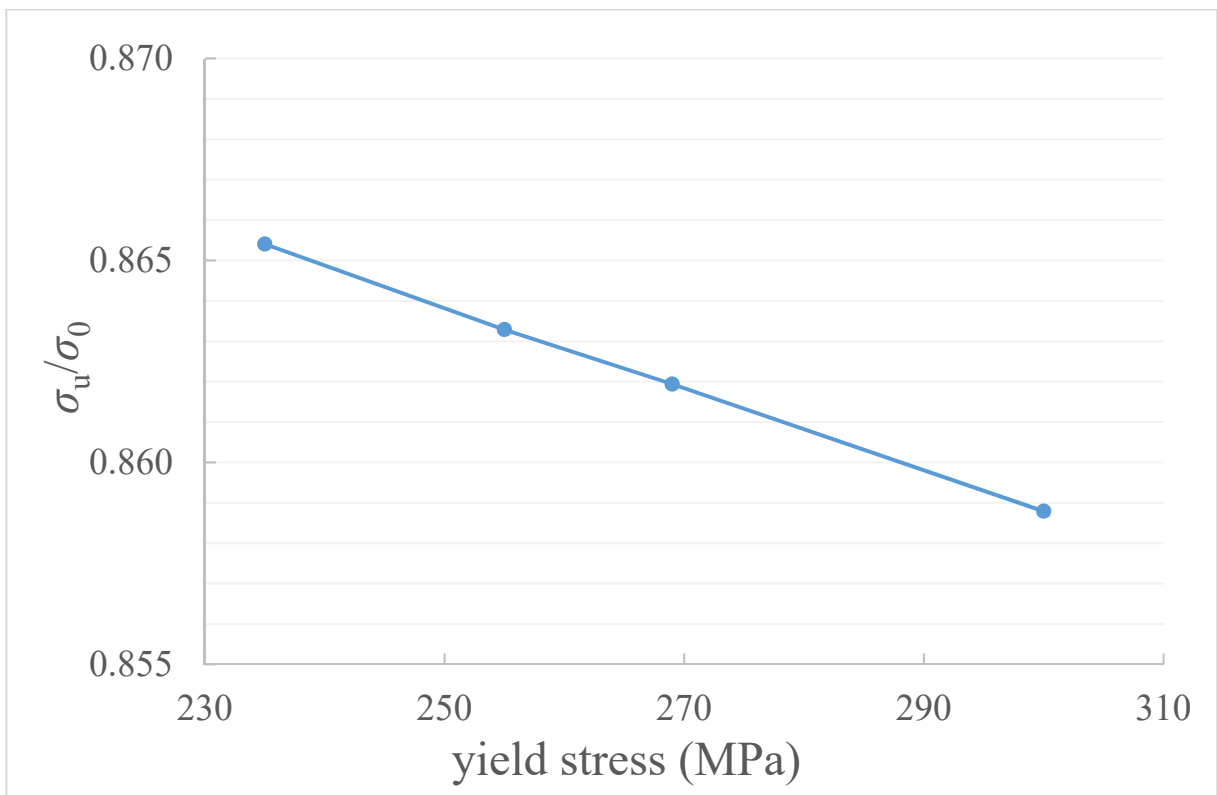


Fig. 4.6 Relationship between residual ultimate strength ratio of corroded tubes to intact ones and tube material yield stress

4.8 Conclusions

In this part, the residual ultimate strength of pit corroded tube members is investigated. At first, it is confirmed that the most severe situation for corroded tube is the pit corrosion occurs on the surface of tube mid span.

Second, the effect of pit corrosion area size is investigated. The effect of corrosion area size in tube axial direction has very little influence on the residual ultimate strength of corroded tube members, otherwise the effect of corrosion area size in circumferential direction has a dominant influence, which is the similar conclusion as the corroded plates that the cross section area reduction is the key parameter to describe the residual ultimate strength of corroded plate and tube members.

Third, cross section area reduction is divided into two independent variables, one is the pit depth, the other is the central angle of corroded area size in the circumferential direction of the tube. These two variables are studied separately. And bases on the numerical simulation results, a simplified formula is proposed to shown the relationship between the residual ultimate strength of corroded tube member and the corrosion depth and size.

Forth, the influence of the tube scantlings is carried out. By modifying the above simplified formula, the effects of L/D and D/t are both taken into consideration.

Fifth, the coupling effect of geometrical initial imperfection is investigated. Three kinds of geometrical imperfection are introduced into the models, and the comparison results verified that the ultimate strength reduction ratios, σ_u/σ_0 , for tube with and without geometrical imperfection are almost the same. That means the geometrical initial imperfection affects the compressive ultimate strength of the corroded tubes in the same way it affects the intact tubes.

Final, the variation of material properties is clarified. Both Young's modulus, E , and yield stress, σ_y , are proved to have limit influence on the ultimate strength reduction ratios. Moreover, the simplified formula proposed in this Section is valid to describe the residual ultimate strength of pit corroded tube members.

4.9 Appendix: mesh divisions for intact and corroded tubes

At first, a tube with the scantling of $10\text{m} \times 2.5\text{m} \times 40\text{mm}$ ($L \times D \times t$) is modelled. A diamond shape of geometrical initial imperfection is introduced into the tube.

$$w = w_0 \cos 3\theta \quad w_0/t = 0.5$$

8 cases with different shell element mesh sizes. In each case the element shape is almost square. The calculation results are shown in Fig. 4.7 and Table 4.13. From the results, the exact value of ultimate strength is 226.4MPa.

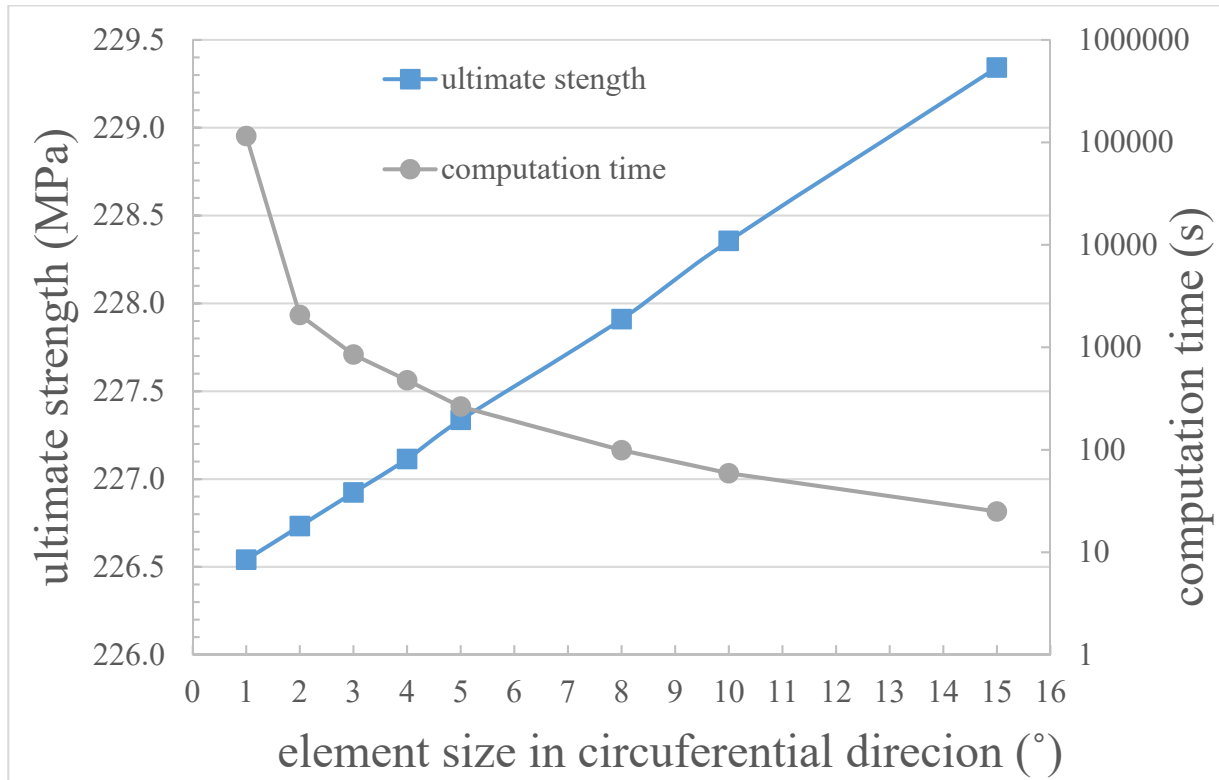


Fig. 4.7 Calculation results of ultimate strength and computation time of models with different element sizes

Consider about the calculation accuracy (the error from the exact value) and computation time together, 4° is applied as the element size in the following calculations, since the difference between 227.2MPa (4° result) and 226.4MPa is enough small and the calculation time is acceptable.

Secondly, the ultimate strength of intact tubes without geometrical initial imperfection is investigated, by changing the ration of w_0/t . The scantling of tubes is shown in Table 4.14. The shell thickness is 40mm for every cases. And the calculation results are shown in Table 4.14. So it is believed that for the tubes in this research, the ultimate strength of intact tubes is the yield stress, 235MPa.

Table 4.13 Calculation results of ultimate strength with different element sizes

Degree	$n_z \times n_\theta$	Element number	F_0 (MN)	σ_0 (MPa)	Error (%)	Computation time (s)
1	400×360	144000	71.17	226.54	0.06	115084
2	200×180	36000	71.23	226.73	0.14	2069
3	134×120	15840	71.29	226.92	0.22	850
4	100×90	9000	71.35	227.11	0.31	477
5	80×72	5760	71.42	227.34	0.41	264
8	50×45	2250	71.6	227.91	0.66	99
10	40×36	1440	71.74	228.36	0.86	59
15	27×24	648	72.05	229.34	1.29	25

cf.) Error = $(\sigma_0 - 226.4) / 226.4 \times 100\%$

Table 4.14 Calculation results of ultimate strength of tubes with different level of geometrical initial imperfection

w_0/t	0.5	0.1	0.01	0.001
L30-D2.5	222.69 MPa	232.65 MPa	234.40 MPa	234.37 MPa
L30-D4.0	226.99 MPa	233.56 MPa	233.56 MPa	233.56 MPa
L30-D1.8	234.71 MPa	234.71 MPa	234.71 MPa	234.71 MPa
L15-D2.5	225.87 MPa	233.73 MPa	234.31 MPa	234.34 MPa
L45-D2.5	218.11 MPa	232.21 MPa	234.50 MPa	234.53 MPa

Thirdly, the effect of pit shape is studied. The corroded part locates on the outer surface of mid span of the tube. Pit shape is assumed rectangular cone. Four kinds of ratio of pit size to depth, l/d , is selected to be,

$l/d=5, 10, 20$ and 40 . Meanwhile, $l/d=5$ is the same as real cases.

The corroded tube scantlings and material properties are as follows,

$L=30\text{m}$, $D=2.5\text{m}$, $t=40\text{mm}$, $\sigma_y=235\text{MPa}$, $E=2.1 \times 10^5\text{MPa}$, $\nu=0.3$.

The pits arrangement is shown in Fig. 4.9. The corroded area size and position is the same in these four cases. The comparison of ‘average stress-global strain’ relationship calculation

results are shown in Fig. 4.8. And the deformation modes and σ_z distribution are shown in Fig. 4.11 and Fig. 4.11, both at ultimate state and post ultimate state. And the overall view of tubes at post ultimate view is shown in Fig. 4.12. From the calculation results, the deformation mode and stress distribution of the four cases are almost the same.

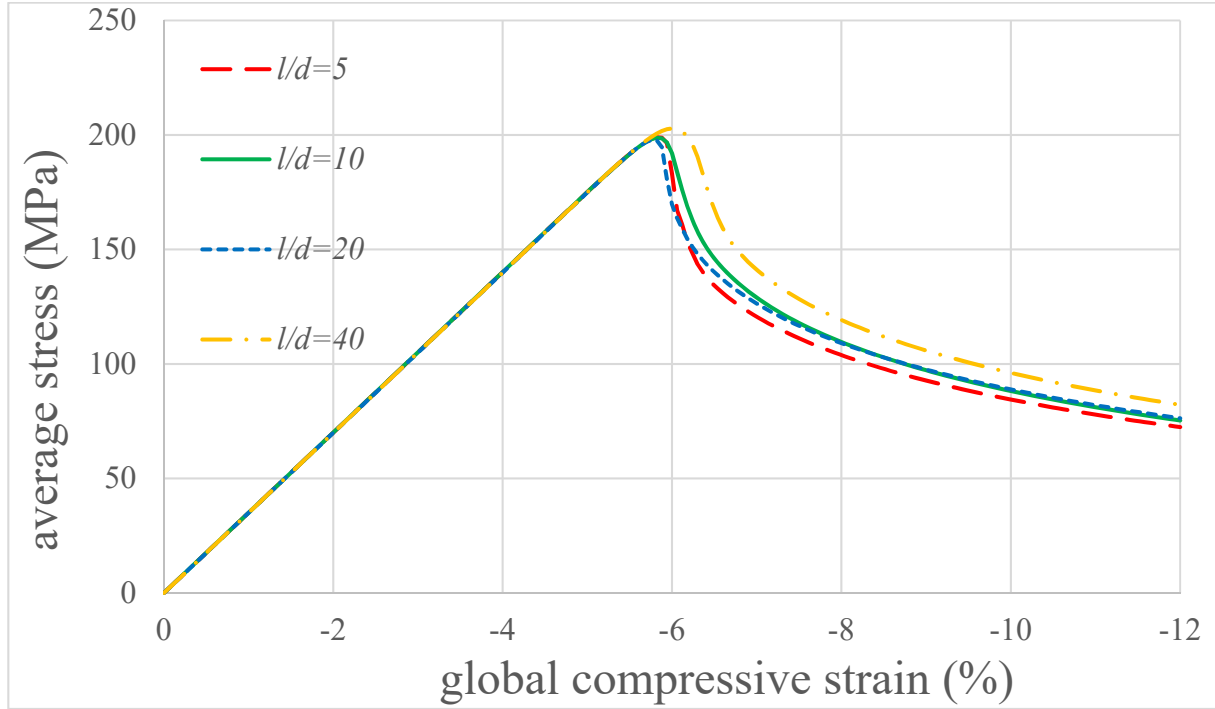
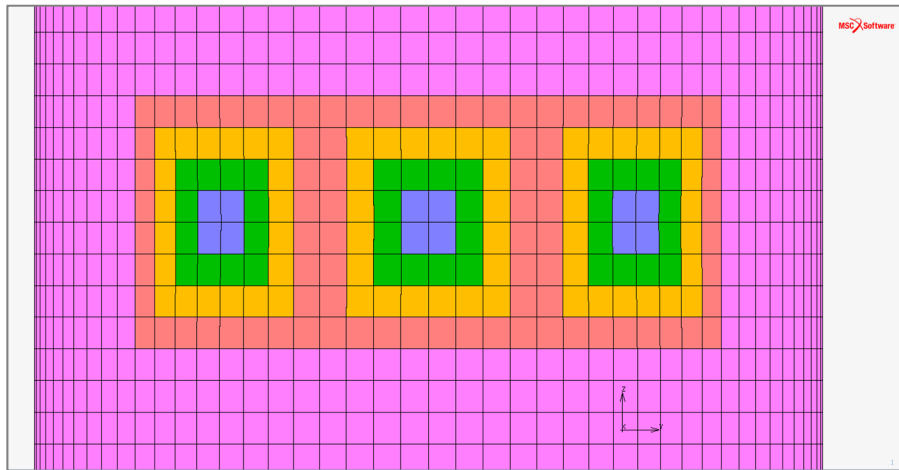


Fig. 4.8 Residual ultimate strength calculation results comparison of corroded tubes with different pit shapes

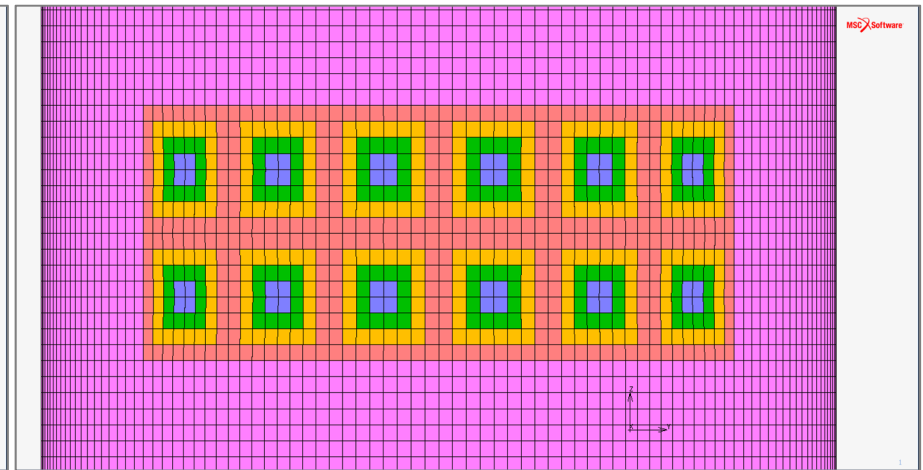
In order to confirm that the residual ultimate strength of corroded tube with pit of $l/d=40$ also give the accurate results, the following additional cases are calculated.

The tube scantling and material properties is the same as above. Two pit shapes are selected, $l/d=20$ and 40. The comparison of ‘average stress and global compressive strain’ relationship calculation results is shown in Fig. 4.14 and Table 4.15, respectively. And the deformation modes and σ_z distribution are shown in

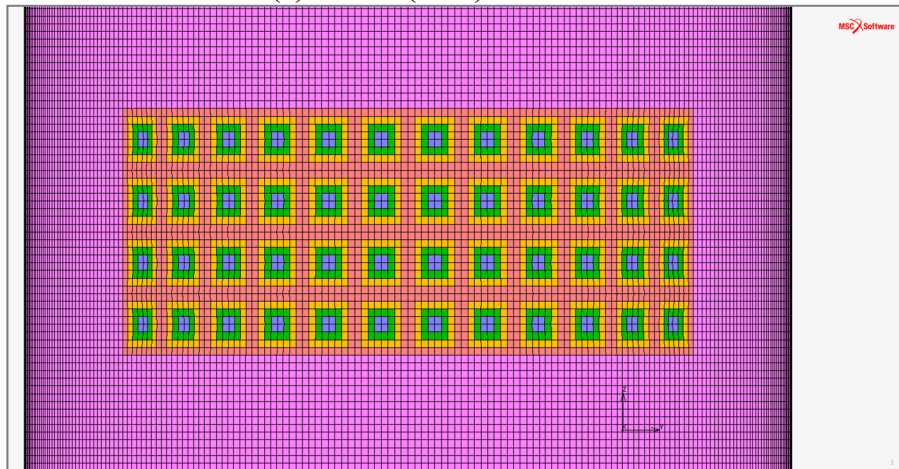
Fig. 4.15, Fig. 4.16 and Fig. 4.17, respectively. The deformation mode is the same both at the ultimate state and post ultimate state. And the ultimate strength is almost the same. So based on the comparison, the calculation results from the cases of $l/d=40$ is valid.



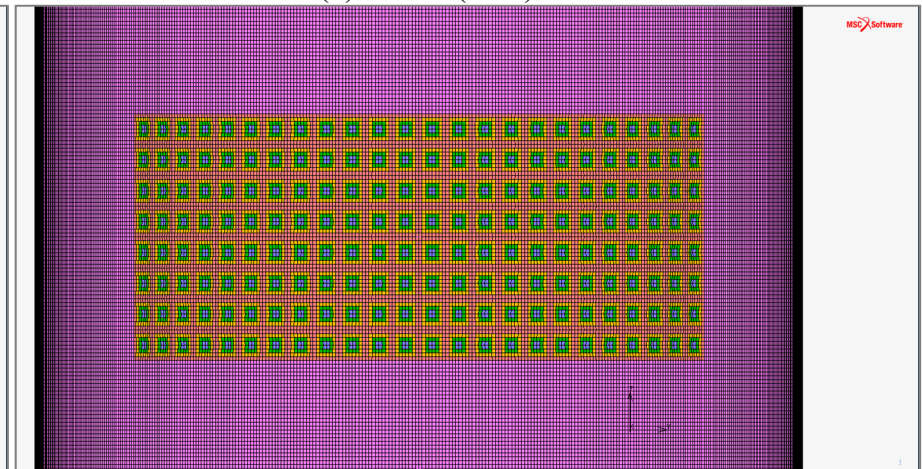
(a) $l/d=40$ (3×1)



(b) $l/d=20$ (6×2)



(c) $l/d=10$ (12×4)



(d) $l/d=5$ (24×8)

Fig. 4.9 Pits arrangement of different pit shapes with the same corroded area size

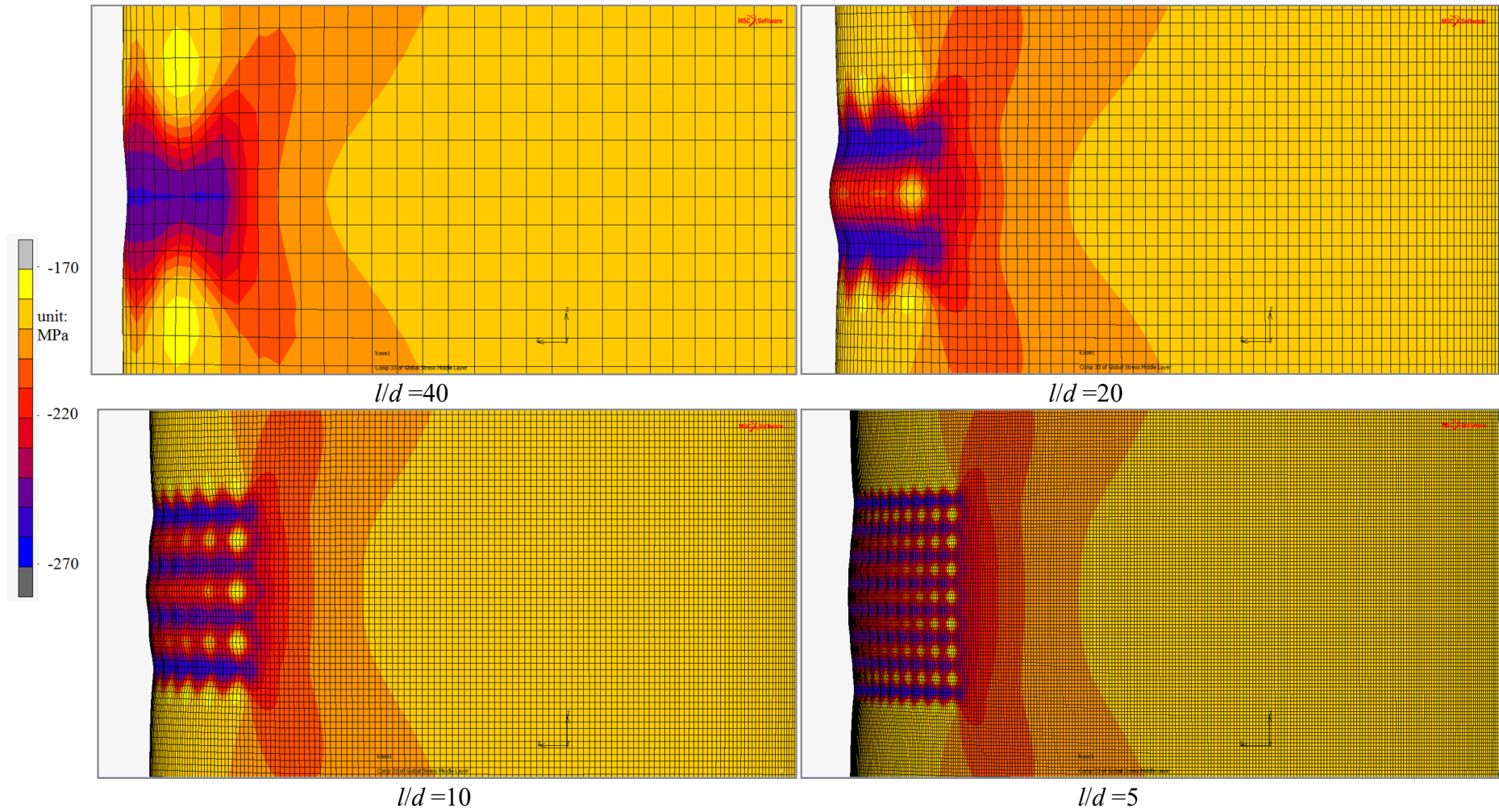


Fig. 4.10 Comparison of deformation mode and σ_z distribution at ultimate state of different pit shape with same corroded area size (factor = 50)

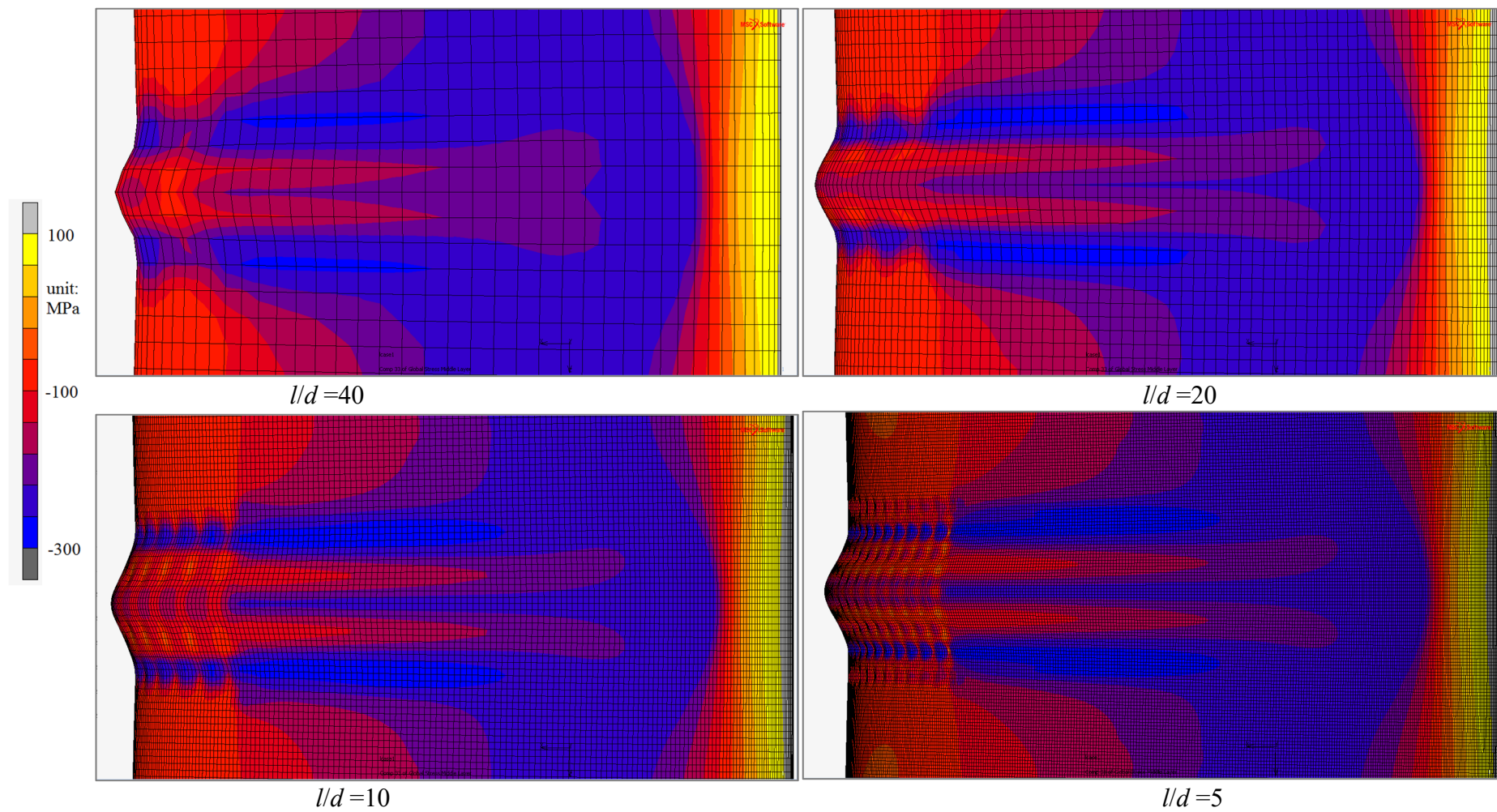


Fig. 4.11 Comparison of deformation mode and σ_z distribution at post ultimate state of different pit shape with same corroded area size (factor = 1)

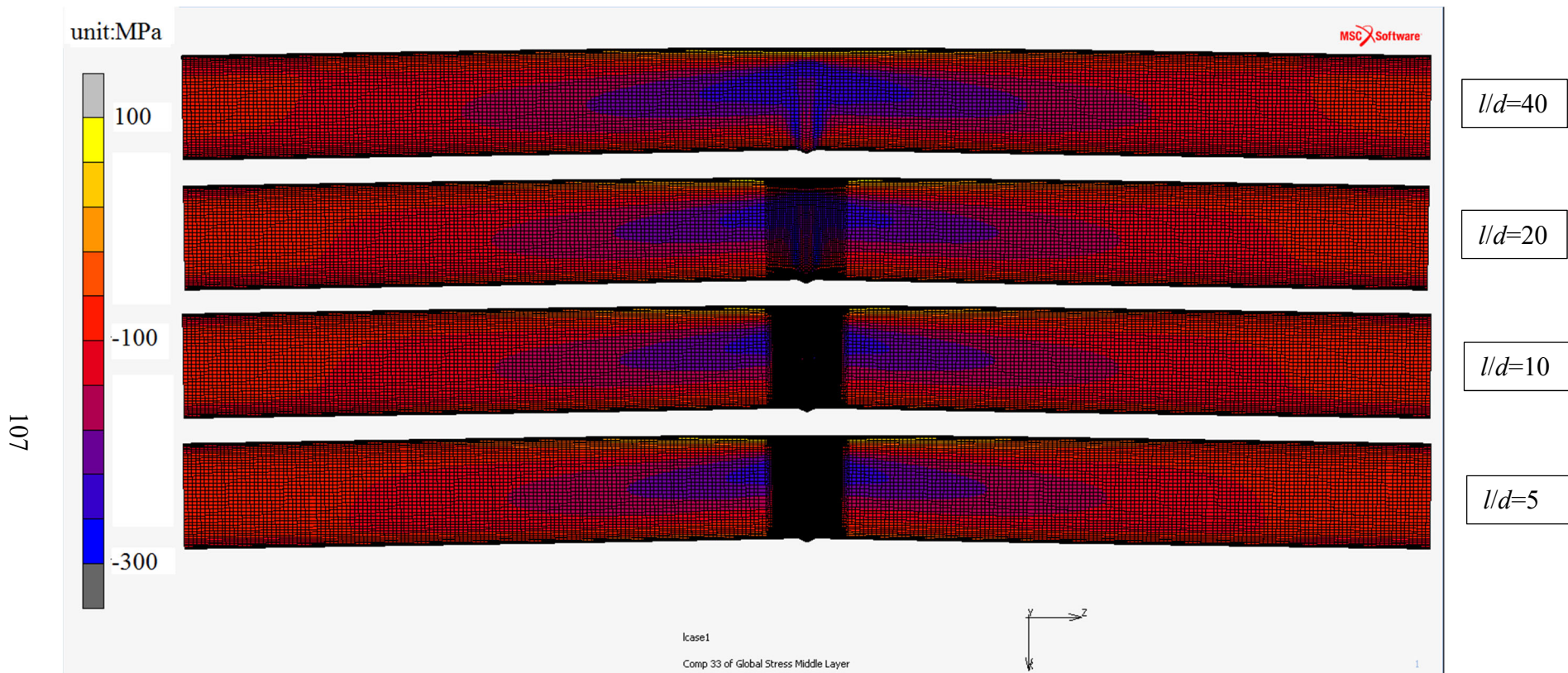
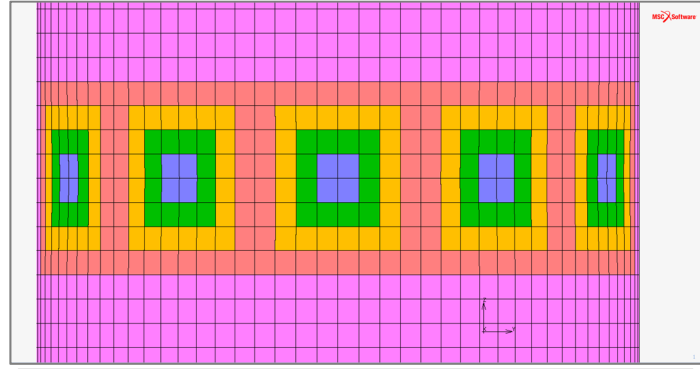
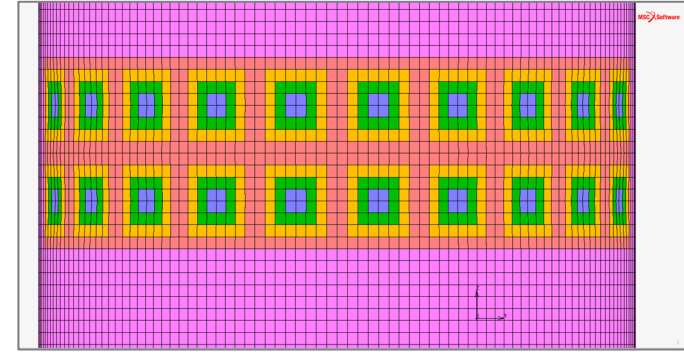


Fig. 4.12 Comparison of deformation mode and σ_z distribution at post ultimate state of different pit shape with same corroded area size, overall view (factor = 1)

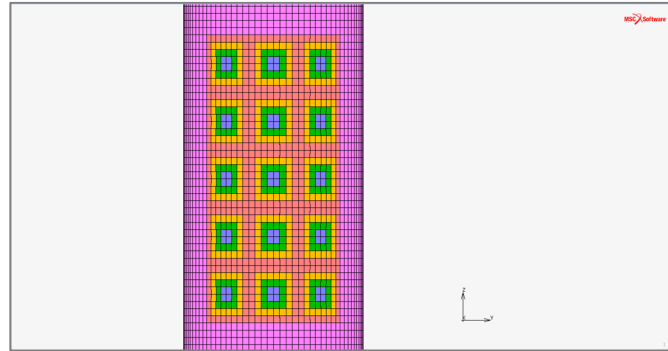
$l/d=40$ (#5×1)



$l/d=20$ (#10×2)



$l/d=40$ (#3×5)



$l/d=20$ (#6×10)

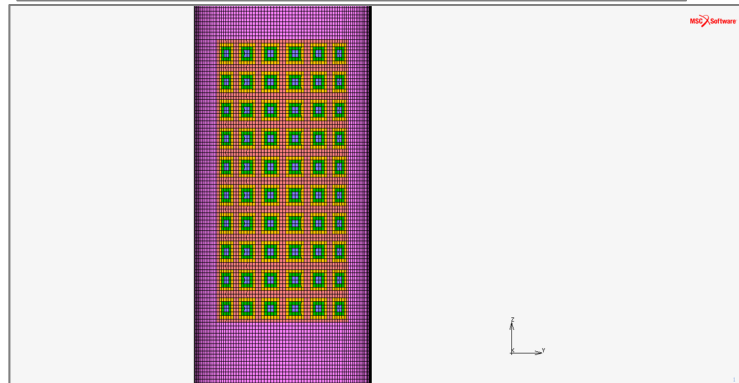


Fig. 4.13 Pits arrangement

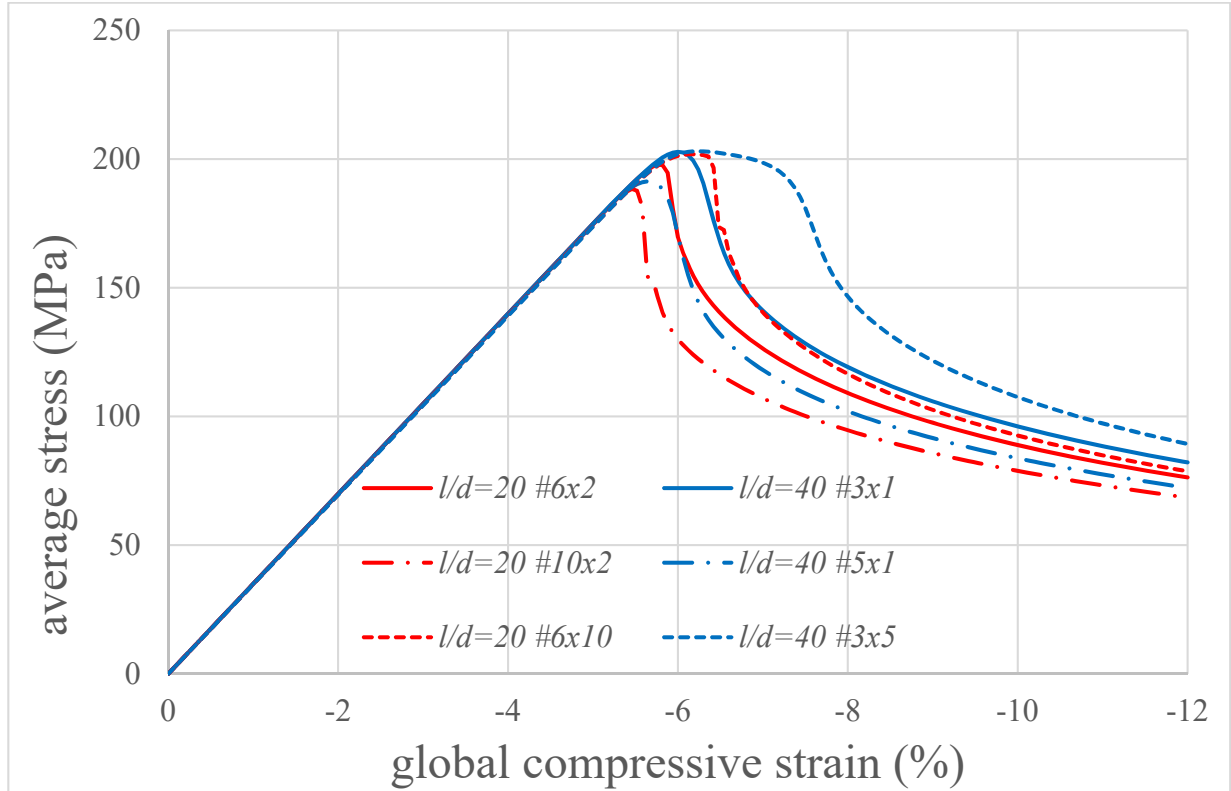
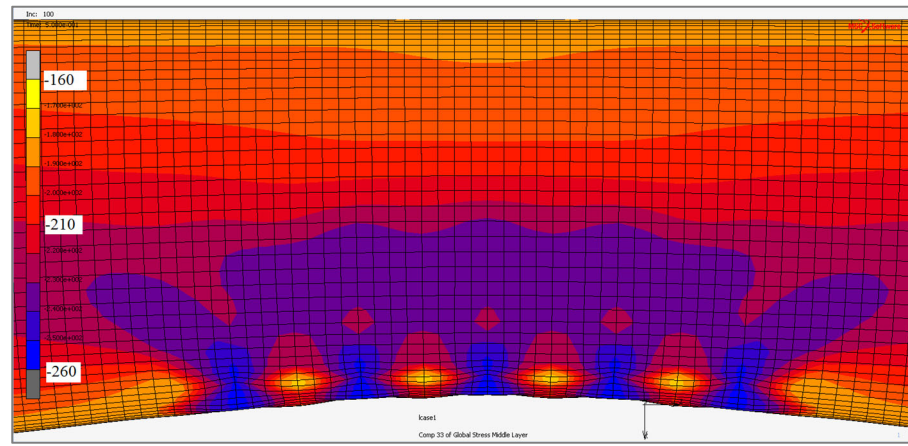


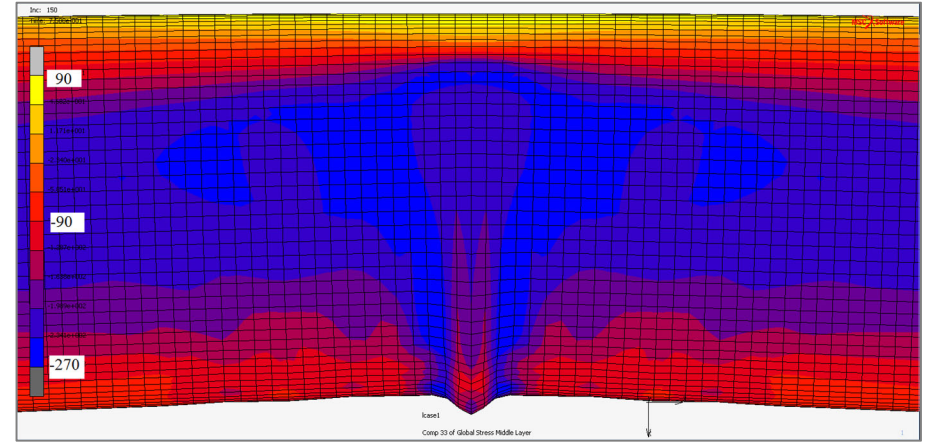
Fig. 4.14 Comparison of ‘average stress and global compressive strain’ relationship calculation results between $l/d=40$ and $l/d=20$

Table 4.15 Residual ultimate strength

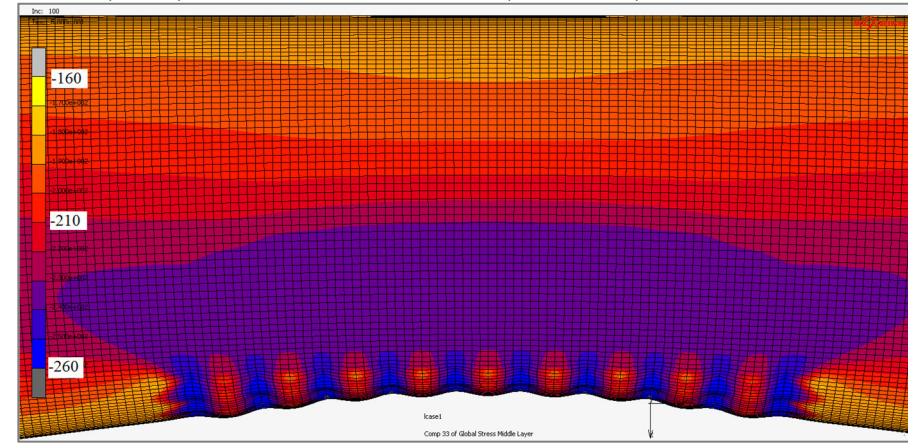
Case	σ_1 (MPa) $l/d=20$	σ_2 (MPa) $l/d=40$	σ_2/σ_1
#3×1 or #6×2	197.85	202.82	102.51%
#5×1 or #10×2	188.39	191.35	101.57%
#3×5 or #6×10	201.89	203.03	100.56%


 $l/d=40$ (#3 $\times$ 5)

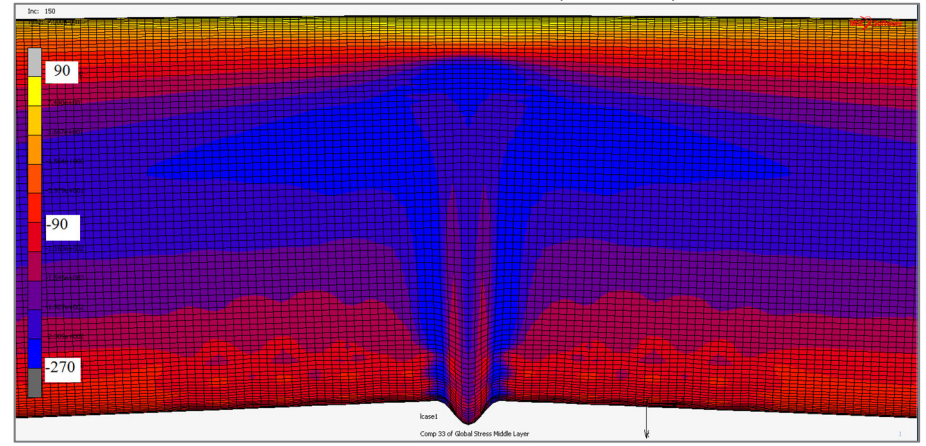
Ultimate state (factor=50)



Post ultimate state (factor=1)

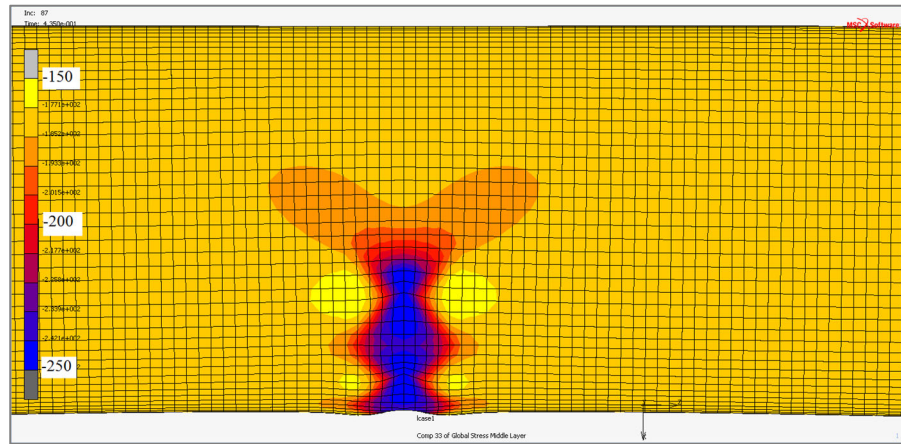

 $l/d=20$ (#6 $\times$ 10)

Ultimate state (factor=50)



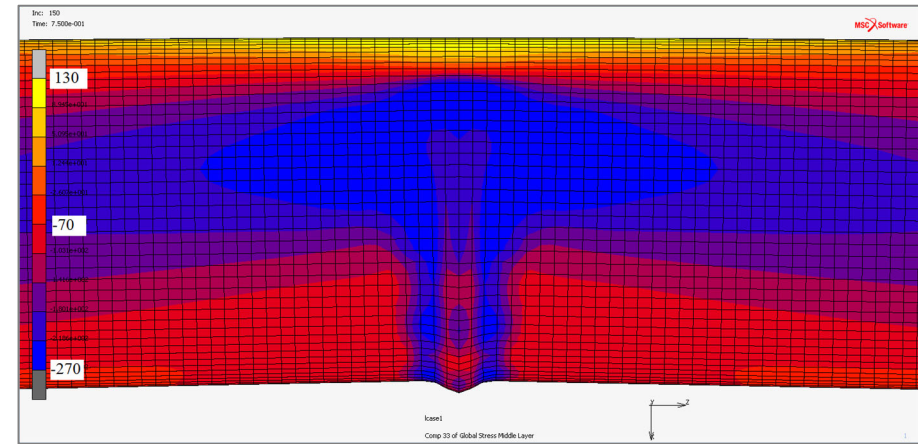
Post ultimate state (factor=1)

Fig. 4.15 Comparison of deformation mode and σ_z distribution at the ultimate state and post ultimate state of Case $l/d=40$ (#3 $\times$ 5) and Case $l/d=20$ (#6 $\times$ 10) (unit: MPa)

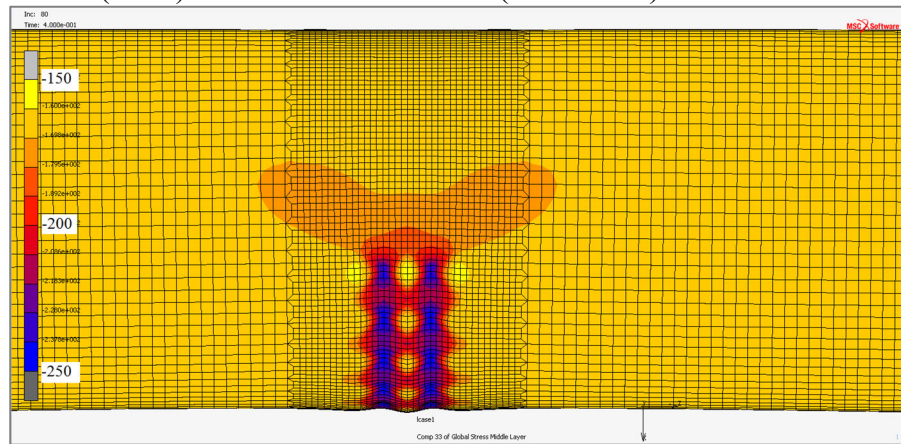


$l/d=40$ (#5 $\times$ 1)

Ultimate state (factor=200)

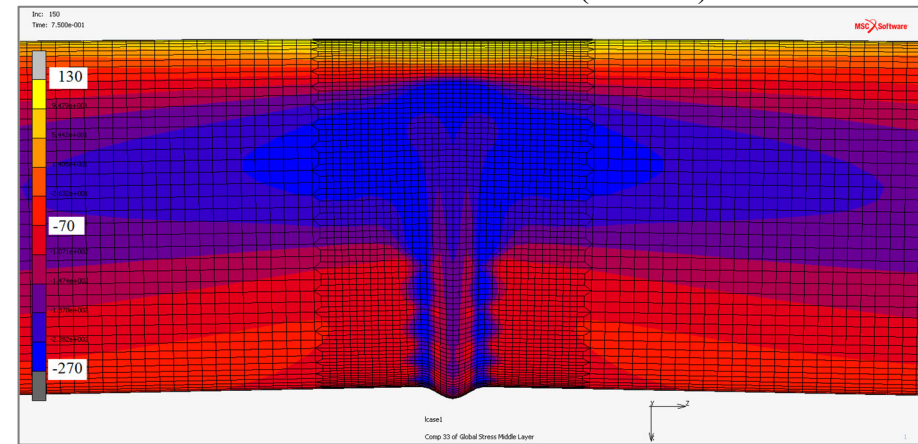


Post ultimate state (factor=1)



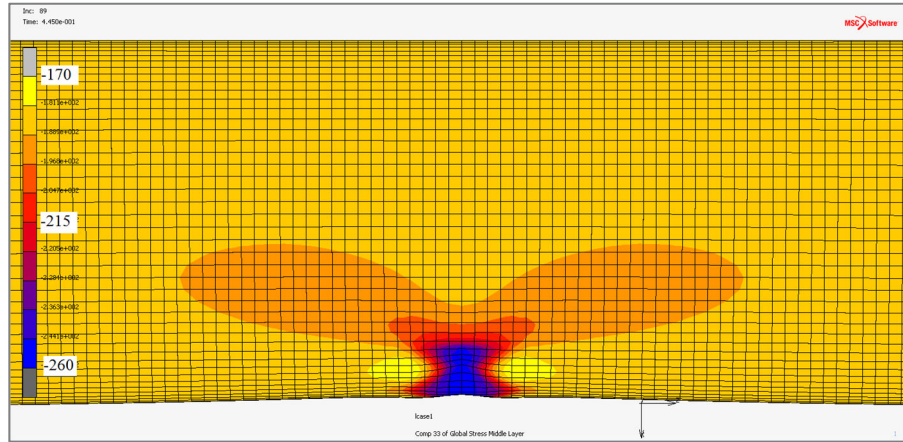
$l/d=20$ (#10 $\times$ 2)

Ultimate state (factor=200)



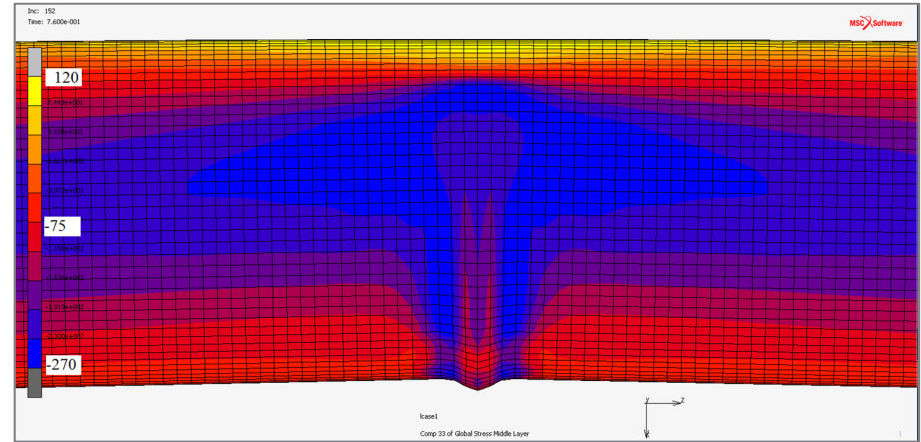
Post ultimate state (factor=1)

Fig. 4.16 Comparison of deformation mode and σ_z distribution at the ultimate state and post ultimate state of Case $l/d=40$ (#5 $\times$ 1) and Case $l/d=20$ (#10 $\times$ 2) (unit: MPa)

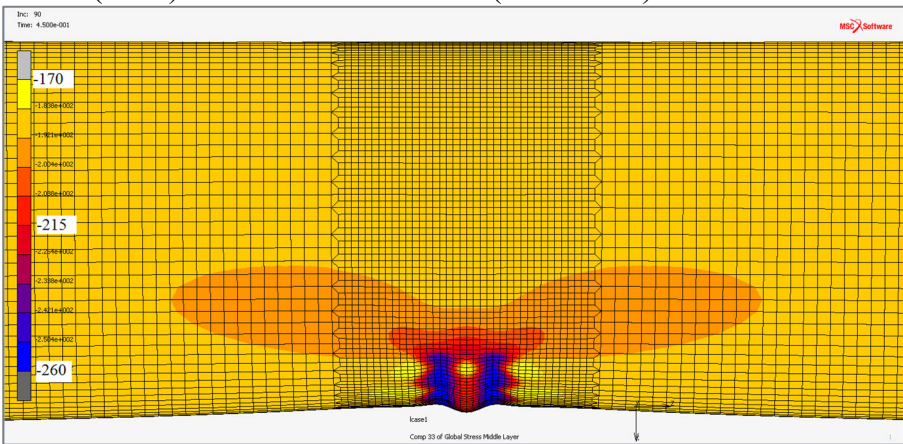


$l/d=40$ (#3×1)

Ultimate state (factor=100)

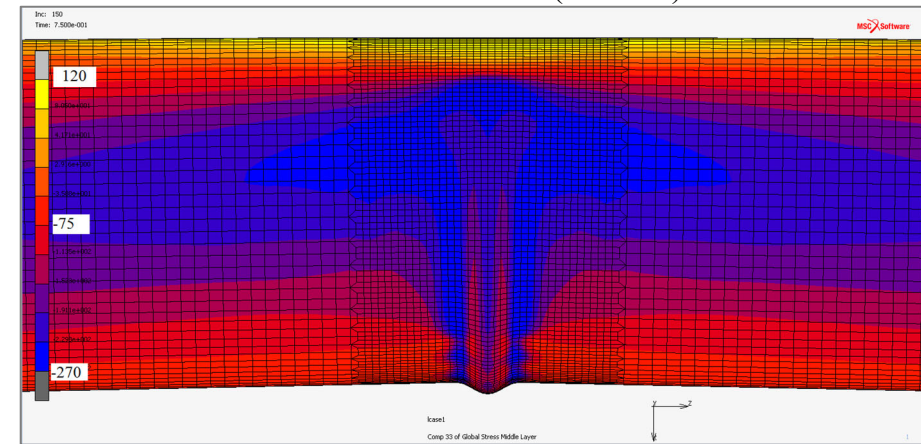


Post ultimate state (factor=1)



$l/d=20$ (#6×2)

Ultimate state (factor=100)



Post ultimate state (factor=1)

Fig. 4.17 Comparison of deformation mode and σ_z distribution at the ultimate state and post ultimate state of Case $l/d=40$ (#3×1) and Case $l/d=20$ (#6×2) (unit: MPa)

Chapter 5. Engineering suggestions based on the residual ultimate strength of damaged tubes

5.1 Introduction

The residual ultimate strength of damaged tube members of offshore structures is investigated due to collision effect and corrosion effect in Chapter 2 and Chapter 4, respectively. And in each chapter, a non-dimensional equation is proposed to describe the residual ultimate strength of damaged tubes.

This chapter contains two parts. In the first part, the probabilistic study of residual ultimate strength of tubes after collision is performed. The main tasks in this part are to calculate the probabilities of failure under the realistic collision scenario. Based on that, the suggestion is provided about how to designate the acceptable approaching velocity of colliding vessel for avoiding fatal damage of tube members in offshore structures. In the second part, the suggestion is provided about the maximum timespan before next inspection.

5.2 Probabilistic analysis of residual ultimate strength for collided tubes

In Chapter 2, a simplified formula is derived to show the relationship between the residual ultimate strength of damaged tube after collision and the non-dimensional parameter, λ . In deriving the simplified formula, all the related parameters are treated as deterministic values. However, in real cases, the common situation is that all parameters have variation range around the design value. So the procedure to obtain the probability of failure after collision damage is introduced in this section.

The variation ranges of tube scantlings and material properties could be measured. And the statistic properties of these two parameters has been investigated by previous researchers such as Gaspar ^[34]. By contrast, the variation range of impact energy could not be measured and estimated easily. And both the impact mass and approaching velocity will influence the impact energy much. So in Section 5.2.1, distribution models of impact mass and approaching velocity are assumed. Then the probability of failure of Basic case is examined in Section 5.2.2. In Section 5.2.3, the limitation of approaching velocity for avoiding fatal damage of tube members are investigated.

5.2.1 The distribution model of collision energy

In this section, the distribution of collision energy is illustrated, both the approaching velocity and the impact mass of supply vessel.

The distribution of approaching velocities of supply vessels is examined based on the reference. It could be assumed to be normal distribution according to Montewka et al ^[56] as shown in Fig. 5.1. And Silveira et al ^[57] and Ståhlberg et al ^[58] have also investigated the velocity distribution of vessels in collision scenarios, such as Fig. 5.2. And the collision velocity is 50%~80% of the ship service speed. So the coefficient of variation (COV: ratio of standard derivation to mean value) of collision velocity in this research is set to be 0.4, and obey the normal distribution.

The impact energy is not only related to approaching velocity but also the impact mass. So the mass is another variable parameter to be considered here. Since the lack of data, as far as the author knows, it is assumed that the distribution of impact mass is because of the consumption of the fuel. So the variation range is not too much. It is assumed the distribution obeys the normal distribution with the COV=0.1.

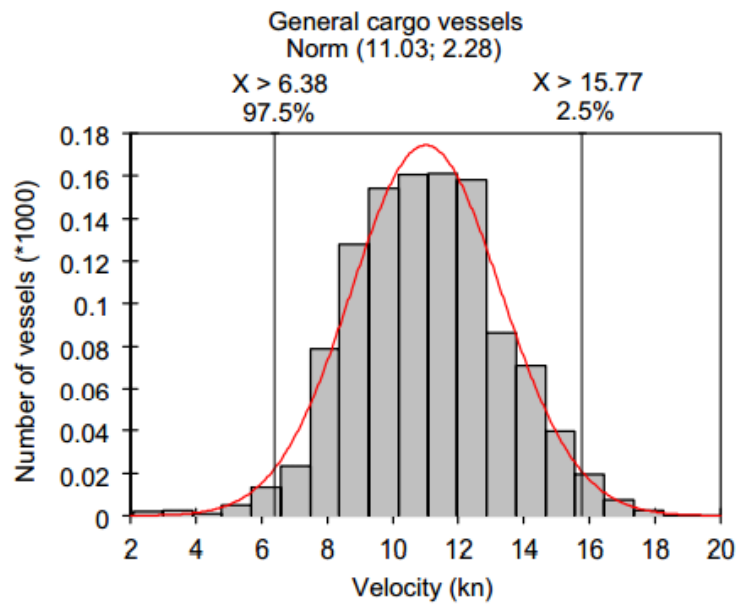


Fig. 5.1 Histograms of velocities for general cargo vessels with distributions fitted by Montewka et al ^[56]

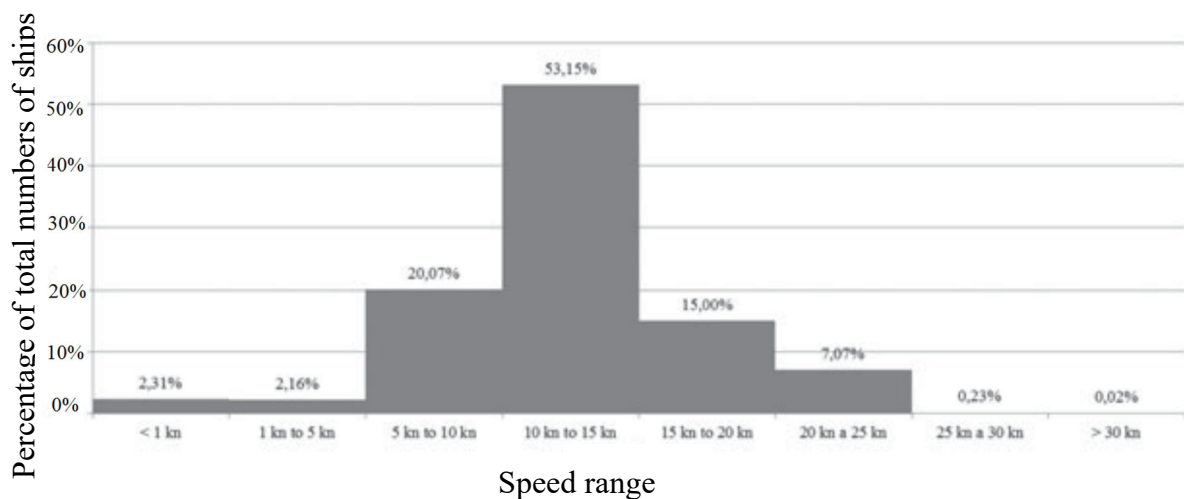


Fig. 5.2 Distribution of ships' speeds by Silveira et al ^[57]

5.2.2 Probability of failure in Basic case

In this section, a method is introduced to calculate the probability distribution of parameter λ , with the application of Monte Carlo method. In order to derive the distributions of parameter λ , the distribution of thickness, yield stress and approaching velocity and mass are shown firstly. The Basic case in Chapter 2 is selected to set up an example. Where, parameter λ was proposed

in Chapter 2 to represent the relation between the residual ultimate strength and the kinematic energy of colliding ship as shown in Equation (2.3).

In the Basic case, the tube scantlings and material properties are as follows,

Tube length,	$L=30\text{m};$
Tube diameter,	$D=2.5\text{m};$
Tube thickness,	$t=40\text{mm};$
Yield stress,	$\sigma_y=235\text{MPa};$
Young's modulus,	$E=2.1\times 10^5\text{MPa}.$

The residual ultimate strength of collision damaged tube can be described by the following equation as shown in Section 2.5,

$$\frac{F_u}{F_0} = e^{-\lambda^{0.687}} \quad (2.3)$$

$$\text{Where, } \lambda = \frac{0.5MV_0^2}{7.575\sigma_y L^{-0.55} D^2 t^{1.55}} \cdot$$

Using Equation (2.3), the distribution of the residual ultimate strength of tube, F_u , can be obtained when the distribution of λ is known.

As shown in Section 2.5, when the value of λ is larger than 0.78, the tube is regarded to be failed. In order to clarify the probability of failure of damaged tubes after collision, Monte Carlo method is applied to calculate the distribution of parameter λ .

The distribution of non-dimensional parameter, λ , is examined as follows,

In calculation of denominator of Equation (2.3), the effect of variation of yield stress of material, σ_y , and tube thickness, t , are taking account. It is because that the variation of tube length, L , and tube diameter, D , is very limited considering the manufacturing procedure of steel tube.

According to Gaspar^[34], the random values (distribution shape, mean value, and COV) of t and σ_y are described Table 1.2 and Table 1.3 in Section 1.1.

In this section, to set up the distribution of thickness and yield stress, the random values proposed by Gaspar^[34] are used.

For instance, in the Basic case, when the thickness selected to be 40mm, the mean value is 40 mm, standard derivation is 2mm ($=0.05 \times 40\text{mm}$) and it obeys the normal distribution which is shown in Fig. 5.3. According this reference, the design value is used as the mean value of thickness, but usually the actual thickness must be larger than the design value. As the safety side estimation, the design value is used as the mean value of thickness in this paper. Of course, in real case, the tube shell thickness variation range should be within 1mm. But, in this research to confirm the effect of variation of thickness, the variation range is enlarged to be within 10mm.

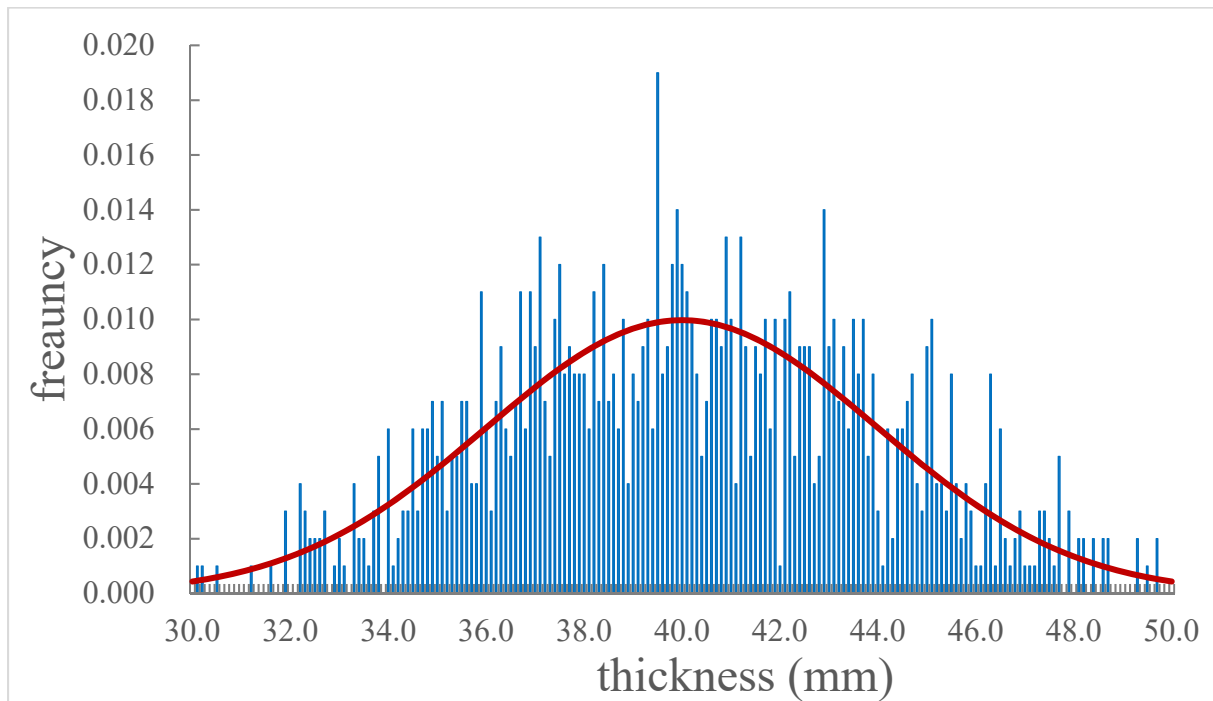


Fig. 5.3 Probability density function of tube shell thickness of random series of values
(Normal distribution, mean value=40mm, standard derivation=2mm)

The distribution of yield stress of mild steel is shown in Fig. 5.4. The design value is 235MPa. It obeys the log-normal distribution with the mean value of 269 MPa and standard derivation is 21.52 MPa ($=0.08 \times 269 \text{MPa}$).

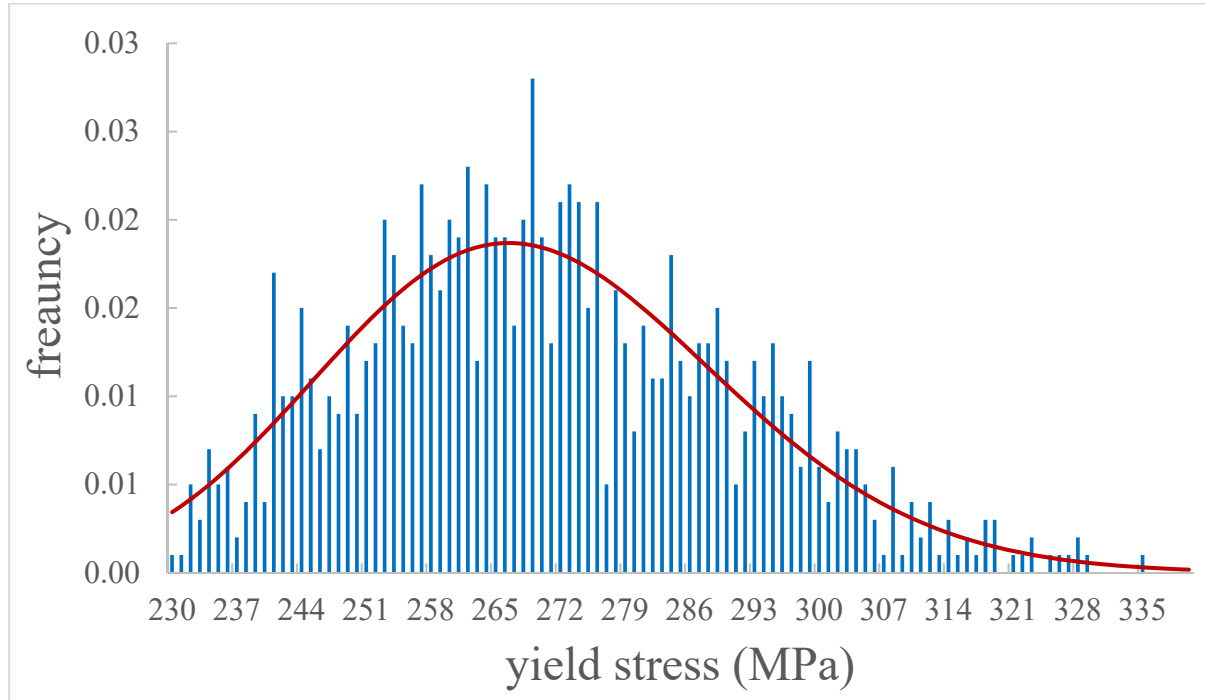


Fig. 5.4 Probability density function of tube material yield stress of random series of values (Log-normal distribution, mean value=269MPa, standard derivation=21.52MPa)

In this calculation of impact energy, which is the numerator of Equation (2.3), the effect of variation of collision velocity, v , is considered while the value of impact mass is assumed to be constant. As stated in Section 2.2.2, although the cruising speed of supply vessel is about 15~20knot, the velocity could slow down below 10 knot when collision might occur. And it is confirmed in Chapter 2 that the value of collision velocity of 5m/s is too high and the ultimate strength of damaged tube is unacceptable after collision. Moreover, when the supply vessel approaches to the platform the velocity will decrease. Therefore, the mean vale of collision velocity is set to 3m/s in Basic case in this section. The normal distribution with mean value of 3m/s, and standard derivation of 1.2m/s is used to describe the probability density function referring the researches of Montewka et al ^[56], Silveira et al ^[57] and Ståhlberg et al ^[58]. The distribution of collision velocity of supply vessel is shown in Fig. 5.5.

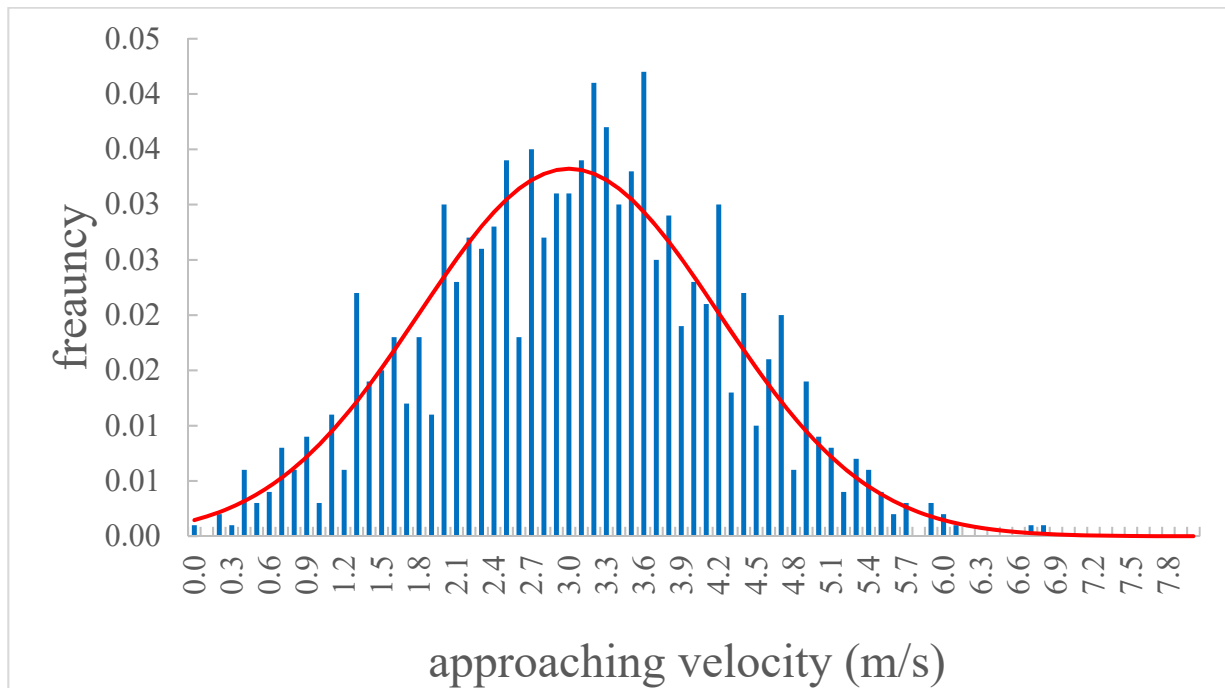


Fig. 5.5 Probability density function of approaching velocity of random series of values
(Normal distribution, mean value=3m/s, standard derivation=1.2m/s)

The distribution of impact mass is shown in Fig. 5.6. It obeys the normal distribution. The mean value is 1000ton and standard derivation is 100ton ($=1000\text{ton} \times 0.1$).

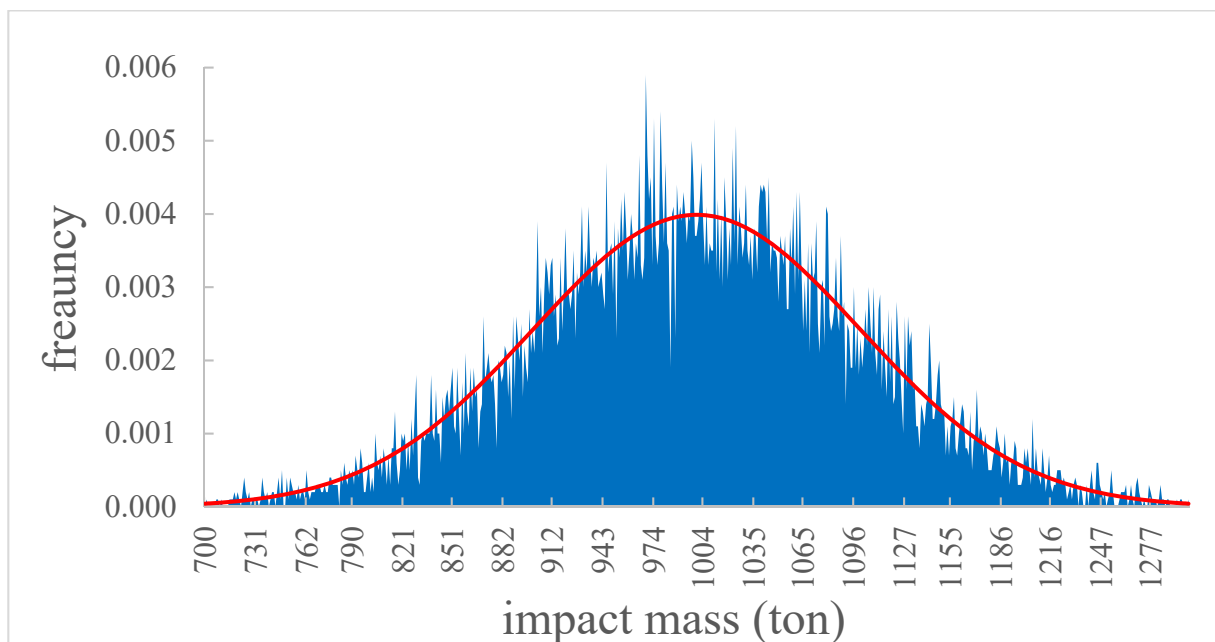


Fig. 5.6 Probability density function of impact mass of random series of values
(Normal distribution, mean value=1000ton, standard derivation=100ton)

As stated above, if the value of λ is larger than 0.78, the tube is regarded to be failed. The tube members should be repaired or replaced. In order to clarify the probability of failure of damaged tube members after collision, Monte Carlo method is applied to calculate the distribution of parameter λ by varying the value of t , σ_y and v . The total number of calculation case is 10000 in this simulation. The distribution of non-dimensional parameter, λ , is shown Fig. 5.7.

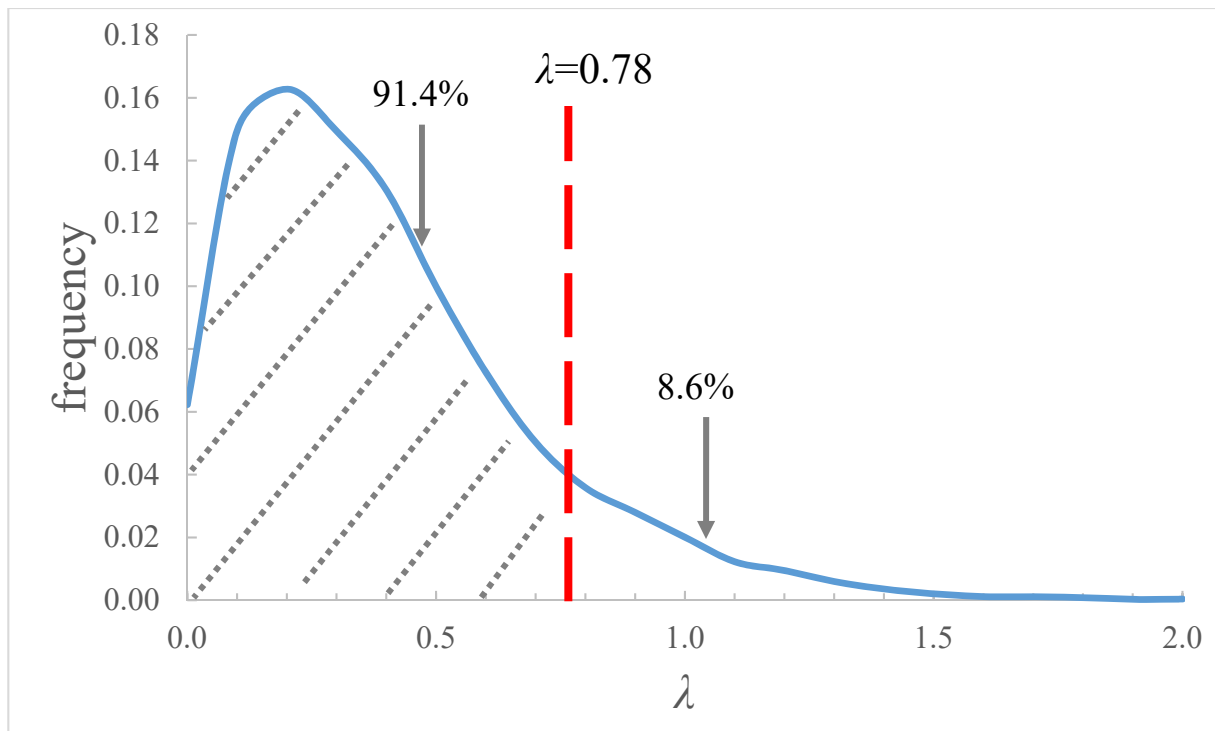


Fig. 5.7 Calculation result of probability density function of non-dimensional parameter λ of Basic case (mean value of approaching velocity is 3m/s)

From this result, the probability of failure of this collision scenario is 8.6%, which equals to the area below the curve of the value of λ larger than 0.78. This result means that, the impact energy in the Basic case is far beyond the bearing capacity of the tube.

5.2.3 The upper bound criteria of approaching velocity

The method to calculate the distribution of parameter λ to estimate the failure possibility of collision scenario is illustrated in Section 5.2.2. In this section the upper bound criteria of approaching velocity is investigated by applying the above method.

In the research of structural strength reliability, most of the criteria of the reliability index is set to be $\sigma \sim 3\sigma$ (one to three times as the standard deviation) from the mean value according to Faulkner ^[64]. And in this case, the damage will lead to collapse of the tube without potential phenomenon, so we should set the probability of failure as small as we could. So 3σ is selected. In this situation, the probability of failure is 0.0013, by assuming the distribution of strength obeys the normal distribution. So in this section, the probability of failure criteria is set to be 0.0013.

Moreover, the distribution of the upper bound criteria of approaching velocity is assumed to obey normal distribution with the mean value of v_{cr} and standard derivation of $0.4 \times v_{cr}$.

The method to calculate v_{cr} is realized by the following procedures by Monte Carlo method as shown in Fig. 5.8,

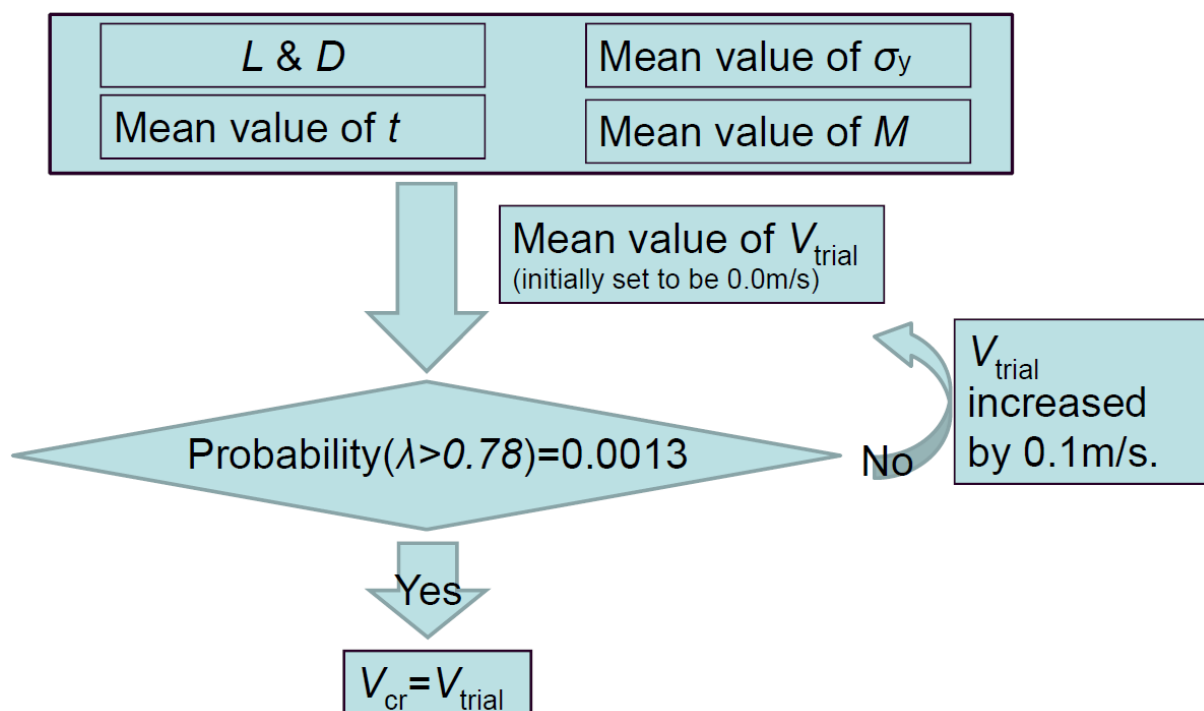


Fig. 5.8 Method to obtain value of v_{cr}

Step 1. Input the values of length and diameter of the tube member;

- Step 2. Input a group of data that obeys the log-normal distribution of material yield stress (such as Fig. 5.3);
- Step 3. Input a group of data that obeys the normal distribution of shell thickness (such as Fig. 5.4);
- Step 4. Input a group of data that obeys the normal distribution of impact mass (such as Fig. 5.6);
- Step 5. Trial to input a group of data that obey the normal distribution of approaching velocity with the mean value of v_{trial} (such as Fig. 5.5, initially set to be 0.0m/s);
- Step 6. Confirm the distribution of parameter λ , then calculate the probability of failure.
- Step 7. If the probability of failure equals to 0.0013, the value of v_{cr} is obtained equals to v_{trial} . If not, return to Step 5 and the value of v_{trial} is increased by 0.1m/s.

By the above six steps the upper bound criteria approaching velocity, v_{cr} , is estimated. The probability density function of non-dimensional parameter λ of Basic case is shown in Fig. 5.9.

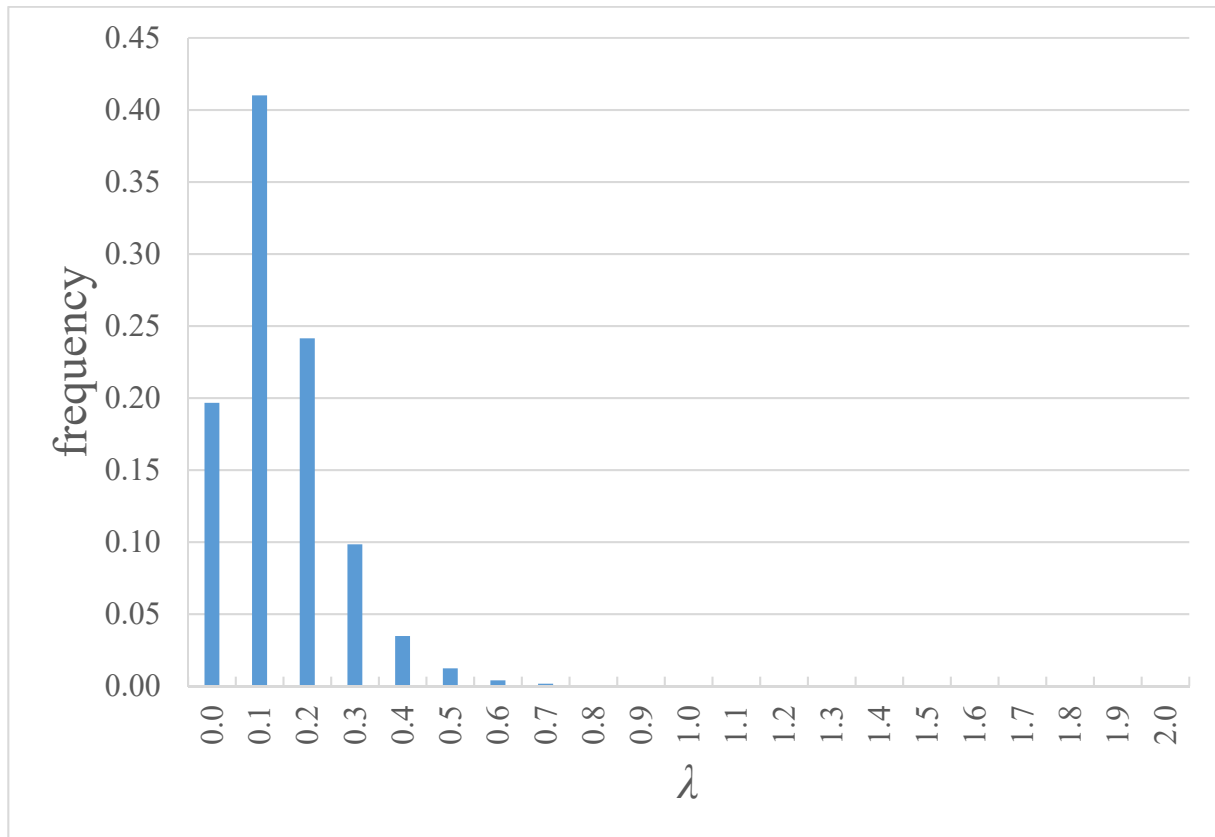


Fig. 5.9 Calculation result of probability density function of non-dimensional parameter λ of Basic case with the failure possibility less than 0.0013

And v_{cr} of other cases are also calculated with the same method, as shown in Table 5.1.

Table 5.1 Calculation results of upper bound criteria approaching velocity ($M_{mean}=1000\text{ton}$)

Case	v_{cr} (m/s)
Basic	1.8
L15	2.3
L45	1.5
D1.8	1.4
D4.0	3.4
T20	1.1
T60	2.9

5.2.4 Conclusions of probabilistic analysis of collided tube

According to the proposed formula Equation (2.3), the probability of failure of tube members is investigated. By applying the Monte Carlo method, and set the probability of failure less than 0.0013, the upper bound value of approaching velocity v_{cr} is obtained. This is a valuable engineering suggestion to provide a reference, when a supply vessel travel approaches close to a jacket platform.

5.3 Estimation of residual ultimate strength for the corroded tubes

In Chapter 4, the residual ultimate strength of pit corroded tubes is investigated. In that research the effects of variation range of the thickness of shell and yield stress of material are studied. And the relationship between the residual ultimate strength of corroded tube and corrosion situation is given by a simplified formula. However, the corrosion situation is sensitive to the environment which is stated in Chapter 1. So some engineering suggestions are provided in this section. The corrosion rate models are listed in Section 5.3.1. Based on an inspection result, suggestions about how to decide next inspection time.in two aspects are provided in Section 5.3.2.

5.3.1 Corrosion rate models in previous researches

There are several series of data measured from ship structures, however, seldom measured data from offshore platforms as far as the author knows. Jacket platform is fixed to the sea bed, the disadvantage is that even if tube members are found to be corroded, it is difficult to repair or replace them, unlike most ships and removable platforms. Based on this feature, over coating or over cathodic protection is always handled. Several mathematical models are created to simulate the relationship between material loss and exposure time, such as, Paik ^[46] and Melchers ^[45].

Time history model of corrosion by Paik ^[46] is shown in Fig. 5.10. This model contains three phases, durability of coating, transition to corrosion, and progress of corrosion. Solid line is for the case in non-immersion environment at liquid (water or oil), and dotted line is for the case in marine immersion conditions at sea.

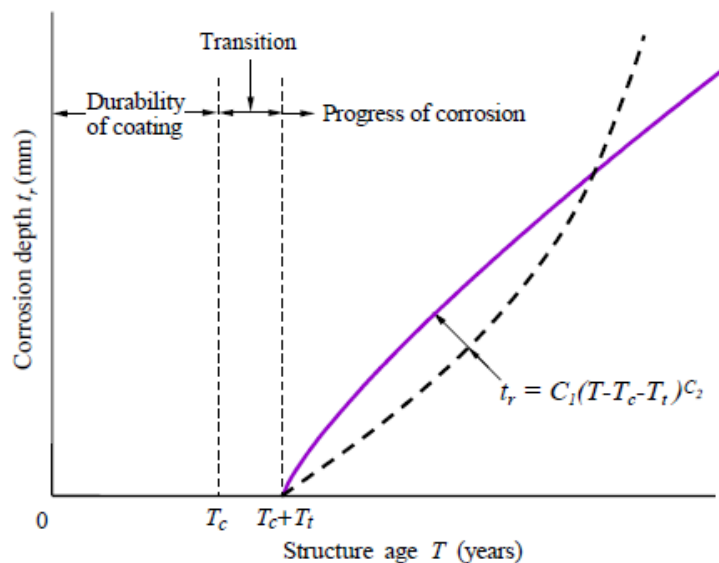


Fig. 5.10 A schematic of the corrosion process for marine structures by Paik ^[46]

Model of Melchers ^[45] is shown in Fig. 5.11. Usually the same period of effective coating is added in the beginning of this model. According to Melchers ^[45], 'Phase 1 is initial corrosion. Phase 2 is oxygen diffusion control period. Phases 3 and 4 are anaerobic activity and food supply procedure.' This model is more complicated compared to the above model.

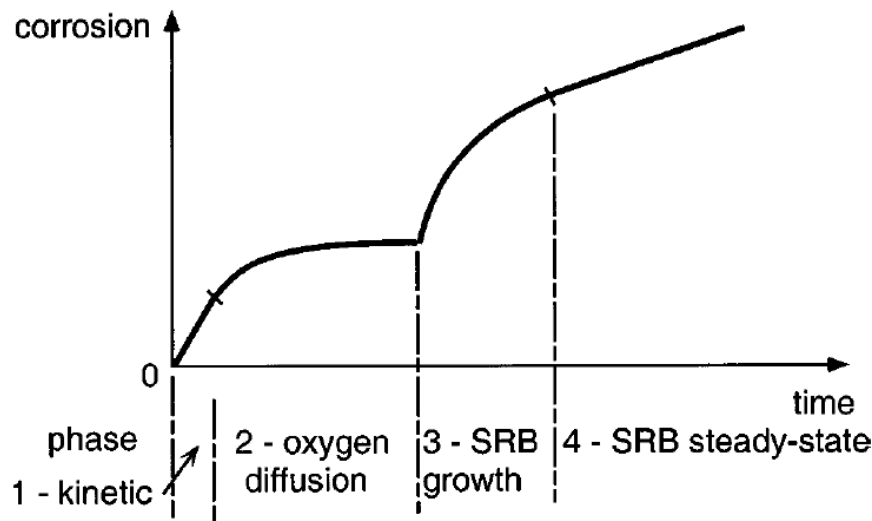


Fig. 5.11 Conceptual model for marine immersion corrosion showing nonlinearity of corrosion behavior with time by Melchers ^[45]

Yamamoto ^[61-63] has also investigated the corrosion rate. According to his experiments, the variation range of corrosion rate is large.

From the measurement results of corrosion loss by Granata ^[55], it is implied that the material loss value of severe situation might be twice of that of medium situation. The material loss value of slight situation might be half of that of medium situation.

5.3.2 Suggestion for inspection timespan

In this section, the inspection timespan is suggested, based on proper corrosion rate model. A proper corrosion rate model is defined to be as follows, this corrosion rate model is proposed according to the data base which is the measurement results from corroded tubes, and the corrosive environment of the target tube and those from the data base should be similar to each other.

As shown in Fig. 5.12, there are three corrosion rate models, A, B and C. The corrosion depth is the maximum pit depth in the severe situation. Model A is similar to the corrosion rate model by Paik ^[46] as Fig. 5.10. Model B is similar to the corrosion rate model by Melchers ^[45] as Fig. 5.11. Model C is an assumed proper corrosion rate, which is proposed based on the measured data from tubes with similar corrosive environment.

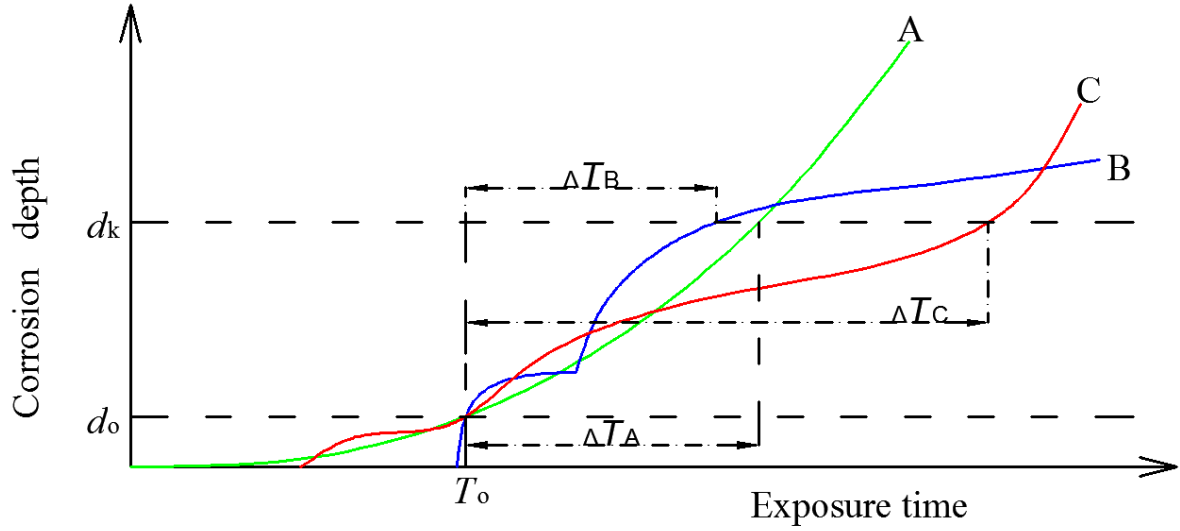


Fig. 5.12 Method to calculate ΔT based on different corrosion rate models

The method to estimate the timespan between two inspections is as follows. In one inspection of exposure time T_0 , corrosion depth is measured to be d_0 . And the maximum acceptable ultimate strength loss is $k\%$, so according to the simplified formula Equation (4.5) proposed in Section 4.5, the acceptable corrosion depth is calculated to be d_k .

$$\frac{\sigma_u}{\sigma_0} = 1 - f\left(\frac{L}{D}, \frac{D}{t}\right) \cdot \eta \quad (4.5)$$

Where, $\eta = \left(\frac{\alpha}{2\pi}\right)^{0.75} \left(\frac{d}{t}\right)^{1.2}$;

$$f\left(\frac{L}{D}, \frac{D}{t}\right) = 0.895 - 2.64 \times 10^{-7} \left(\frac{L}{D}\right) \left[10000 - 127 \left(\frac{D}{t}\right) + 1.73 \left(\frac{D}{t}\right)^2 \right] ;$$

α is the center angle of corroded area, and d is the depth of pits;

L , D and t is the length diameter and thickness of the tube, respectively.

It takes T_0 and T_k times for the tube to be corroded with the corrosion depth of d_0 and d_k , respectively. So the maximum timespan between T_0 and T_k could be estimated to be ΔT_A , ΔT_B and ΔT_C for Model A, Model B and Model C, respectively. And if ΔT is larger than the regular

timespan, 5 years for example, the next inspection could be performed as plan. If ΔT is smaller than the regular timespan, the next inspection should be performed no later than T_k .

However, for the real cases, the timespan between inspections of offshore structures is a fixed value in maintenance, for example ΔT_M . So, the application of ΔT needs some modification, as follows,

If $\Delta T < \Delta T_M$, the measured corroded structure must be repaired in this inspection.

If $\Delta T > \Delta T_M$, the measured corroded structure could be ignored in this inspection.

Almost all the corrosion rate models, such as the two referred in Section 5.3.1, are based on the measurement data from ship structures. That leads to a doubt whether these models are suitable for offshore structures. The corrosive environment is different between ship structures and offshore structures. So a proper corrosion rate model is necessary to derive a reasonable value of timespan between two inspections.

A method to obtain more accurate corrosion rate model is proposed as follows. As soon as one jacket platform is decided to set up in a certain ocean area, several specimens should be settled in the same area. The specimens are manufactured with the same material as the tube members. All the specimens are divided into two groups. Specimens in one group is with coating, in another group is without coating. And the effective years of coating and corrosion level of the specimens could be easier measured. As shown in Fig. 5.13, for example, the inspection result is that the corrosion first occurs to specimen without coating, specimen with coating and tube members is 0 year, 2 year and 5 year, respectively. So the corrosion level of the specimens is 3~5 years advanced than the real structures.

The disadvantage of the above method is as follows. It is hard to remain the position of the specimens. So this problem could be solved, the above method is a good choice to predict corrosion level of tube members of fixed jacket platforms.

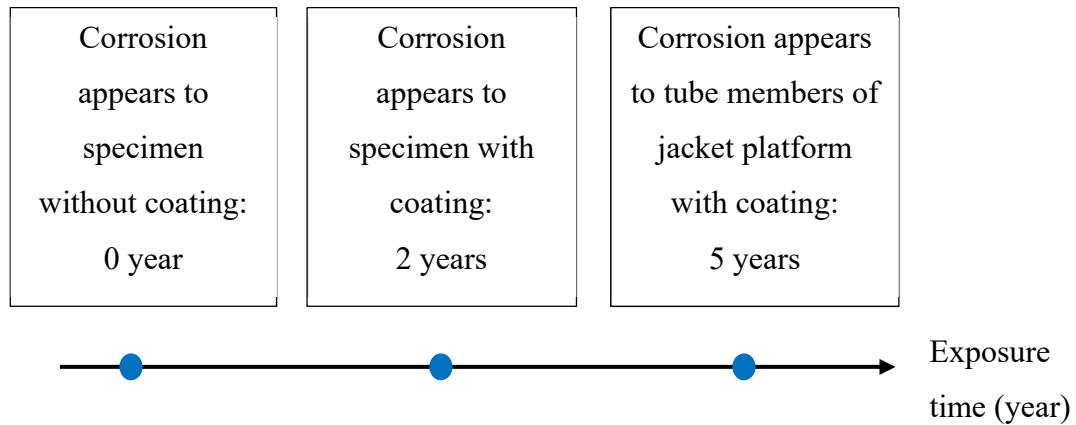


Fig. 5.13 Time history of corrosion first appearance

5.3.3 Conclusions of estimation of corroded tube

In Section 5.3, the importance of an accurate corrosion rate model to estimate the corrosion level is illustrated, since the residual ultimate strength of corroded tube is highly dependent on the corrosion level. And the way how to predict and decide the timespan between two inspections is proposed.

5.4 Conclusions

In this chapter, several meaningful suggestions are provided based on the research of residual ultimate strength of damaged tube, both for collision effect and corrosion effect.

For collision effect, the probability of failure of one certain collision scenario could be calculated by Monte Carlo method. And the upper bound approaching velocity of supply vessel is suggested. For corrosion effect, the proper timespan of inspection is suggested. And the necessity of an accurate corrosion rate model is discussed and a method is proposed to obtain an accurate corrosion rate model.

Chapter 6. Conclusions and future research

In this chapter, the researches in this thesis is concluded in Section 6.1. And the future research is stated in Section 6.2.

6.1 Conclusions

Jacket platform is fixed to a certain ocean area and it is difficult to be moved from one place to another. The substructures of jacket platform are usually made of circular tubes. Therefore, the residual ultimate strength of the tube members to bear the axial compression is important and worth to be studied. The residual ultimate strength of tubes is investigated in this dissertation. Two effects are mainly discussed, they are respectively collision effect and corrosion effect.

In Chapter 2, the residual ultimate strength of damaged tube due to collision effect is studied. Collision effect is a dynamic phenomenon. A non-linear FEA software LS-Dyna is applied for numerical simulation. First, parametric study is performed by changing the tube scantlings and impact energy. Second, the effect of collision position in the axial and circumferential direction of tube is investigated. Third, the effect of the shape of impact object and the effect of energy component are investigated. Then, a parameter, λ , is proposed to be a factor, which consists of the length, diameter and thickness of the tube, the yield stress of material and the mass and velocity of the impact vessel. By this parameter, λ , a simplified formula is derived to show the relationship between the residual ultimate strength of collided tube and the parameters in a collision scenario. Next, the applicability of the proposed simplified formula is examined by introducing the variation range of the thickness of the tube, the yield stress of material and the approaching velocity of impact. Final, with comparing to the API rules, whether the residual ultimate strength of damaged tube is acceptable or not is judged. According to the comparison results, if the value of λ is larger than 0.78, the residual ultimate strength of tube member is not acceptable, and the tube member should be repaired or replaced.

In order to investigate the residual ultimate strength of pit corroded tube, a modeling method is needed to be developed to model pit corroded part by shell elements. So that the numerical simulation is efficient. Plate members is simple case and with smaller scantlings.

In Chapter 3, the residual ultimate strength of pit corroded plate is studied. In this study, MSC.Marc is applied to perform numerical simulations. At first, the method is developed to use large size of shell elements to model the pit corroded part of structures. The ultimate strength of shell element models is compared with the solid element models. Good agreement is achieved so that the validity of this modeling method is confirmed. Second, the effects of following factors are examined to have limit influence on the residual ultimate strength of pit corroded plate, these factors are the effects of pit shape, corrosion position, the ratio of length to breadth of plate, size of corroded area in length direction of the plate. And it is found that if the plate is corroded in the corner part, the residual ultimate strength is the most severe. Third, the coupling effect of geometrical initial imperfection is investigated. Forth, the cross section area reduction is the dominant parameter to influence the residual ultimate strength of corroded plate. With the help of effective width, the equivalent cross section area reduction is proposed. This parameter unifies the independent variable of plates with different ratio of thickness to breadth (thin plate or thick plate). Final, a simplified formula is proposed to show the relationship between residual ultimate strength of pit corroded plate and the equivalent cross section area reduction.

In Chapter 4, the residual ultimate strength of pit corroded tube is studied. Numerical simulation is also performed in the FEA software, MSC.Marc. By application of the modeling method proposed in Chapter 3, the pit corroded tube members are modeled. At first, three parameters is selected to describe the corrosion situation of tube, the longitudinal length of corroded area, l_c , the center angle of corroded area, α and the depth of pits, d . Second, effect of corrosion position is examined that the most severe situation is that the tube is corroded in the middle span. And the effect of corroded area size in the axial direction of tube has limit influence on the residual ultimate strength of pit corroded tube. Third, the effects of the parameter α and d are investigated separately. Forth, the coupling effect of geometrical initial imperfection is examined, the ratio of residual ultimate strength of corroded tube to intact one keeps stable when changing the amplitude of geometrical initial imperfection. Next, a simplified formula is proposed to show

the relationship between residual ultimate strength of pit corroded tube and parameter α and d . Then, a modification factor is introduced to the simplified formula due to the effect of tube scantlings. The effect of tube scantlings is very limit. Final, the applicability of the proposed simplified formula is examined by introducing the variation range of the thickness of the tube and the yield stress of material.

In Chapter 5, the engineering suggestions are provided based on the researches of residual ultimate strength after damaged. In the research of collided tube, Monte Carlo method is applied to calculate the probability density of parameter λ . The independent variable groups are the thickness of the tube, the yield stress of material, the approaching velocity and impact mass of supply vessel. 10000 values of each groups are selected to calculate parameter λ . By changing the mean value of approaching velocity and setting the probability of failure to be 0.0013, a suggestion of upper bound limit for approaching velocity is derived. In the research of corroded tube, it is confirmed that the key point is to develop an accurate model of corrosion rate with exposure time. And the suggestion is provided to the maximum allowable timespan between two inspections.

The numerical simulation results and simplified formulae could be reference in the design stage for tube scantlings, especially the tube shell thickness, with knowing the approximately the potential impact energy for collision effect and an enough accurate relationship between the corrosion depth and exposure time. On the other hand, for maintenance, the simplified formulae are tools to predict residual ultimate strength rapidly. And considering the residual ultimate strength of damaged tubes, engineering suggestions could be carried out to prevent the tube from acceptable damage.

6.2 Future research

As for the future research of collided tube, a deformable ship structure is helpful to derive more accurate formula to predict the residual ultimate strength of damaged tube. And the relationship between residual ultimate strength of damaged tube and the effect of impact point offset in tube radius direction is worth to be studied.

As for the future research of corroded tube, the key point is how to obtain an accurate corrosion rate model for offshore structures. This will be highly based on measurement.

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