공학석사학위논문

Collapse Strength of Thick-walled Steel Pipe
Considering Post-Buckling Behavior

후좌굴 거동을 고려한
두꺼운 강관의 극한강도 평가

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ABSTRACT

Collapse Strength of Thick-walled Steel Pipe Considering Post-Buckling Behavior

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In this research, failure modes of thick-walled and thin-walled pipes were compared based on mechanics of buckling theory and were verified using Finite Element Analysis (FEA). Also, the prediction equation which was used for the design of thick-walled pipe was suggested.

The offshore steel pipe is vulnerable to external pressure, particularly during the construction phase. Therefore, the local buckling and collapse should be considered when designing a offshore steel pipe. The collapse is governed by the material and geometric properties of the steel pipe. The collapse strength of thin-walled pipe which has the failure mode relevant to linear elastic properties can be evaluated using analytic approach. However, the failure mode of thick-walled pipe with diameter to wall thickness (D/t) ratios below 15 is influenced by nonlinear inelastic properties. There is limitations to involve these properties when analytic method is used. A total

of 360 cases were carried out, 3-Dimensional FEA considering material and geometric nonlinear properties, for accurate prediction of the collapse strength of thick-walled pipe. The results demonstrated that the failure mode of thick-walled pipe was influenced by post-buckling behavior. This behavior was relevant to material and geometric nonlinear properties, and brought the effect that the collapse strength was increased. A prediction equation for evaluating the collapse strength of thick-walled pipe was proposed. It was shown that the collapse strength of thick-walled pipe was more influenced by material properties than initial imperfections. This research suggests that parameters of material model are accurately considered when designing a thick-walled pipe.

Key words : Thick-Walled Pipe, Collapse, Local Buckling, Collapse Strength, Post-Buckling Behavior, Prediction Equation

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1 Introduction

1.1 Backgrounds

The resources of onshore and shallow-water are being rapidly depleted by growth of global energy consumption. Accordingly, mining of deep-water resources that was not considered as an economical problem is increasing. Figure 1 and Figure 2 show the growth in global oil consumption and the extraction of deep-water resources, respectively. The Perdido SPAR platform, which has a maximum water depth of 2450m, is the deepest offshore platform currently in operation and deeper offshore platforms are planned in the near future. Therefore, the importance of design of offshore steel pipe which is located in deep-water is increasing.

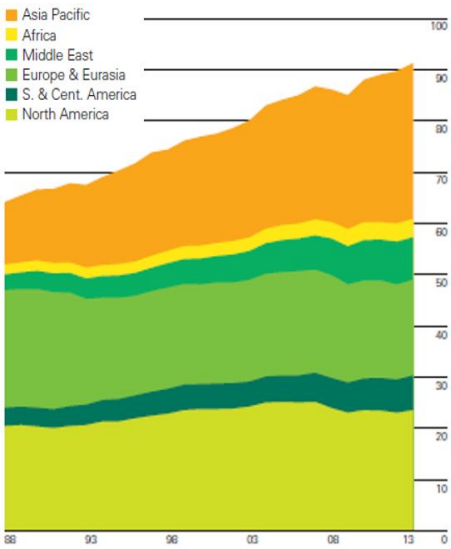

Figure 1 Growth in Global Oil Consumption by Region (BP, 2014)

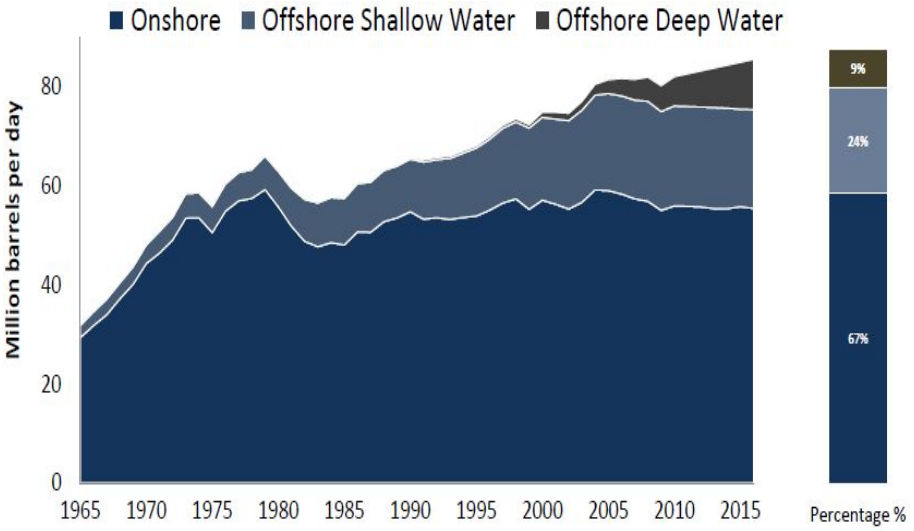

Figure 2 Growth of Deep-Water Resource Activity (Infield, 2013)

The safety of the pipes which is installed in deep-water is influenced by external pressure, because the steel pipes have no internal pressure in the construction phase. Accordingly, the local buckling and collapse should be considered when designing a offshore steel pipe. If an offshore steel pipe collapses, it can cause significant environmental damage and economic loss. Therefore, accurate limit state assessment should be performed.

According to mechanics of buckling of steel pipe, the buckling of thin-walled pipe under external pressure is governed by the elastic behavior of the materials used, whereas buckling of thick-walled pipe is governed by the plastic behavior of materials. Timoshenko and Gere (1961) suggested that following classical design formulation for a long and circular cylindrical shell similar to thin-walled pipe. The formulations were defined as follows:

$$\triangle_0 = \frac{2(D_{\max} - D_{\min})}{D_{\max} + D_{\min}} \tag{1}$$

where, $\triangle_0$ is the ovality which means that initial imperfections, D_{max} and D_{min} are the maximum and minimum diameters of the cross-section.

$$\mu = 1 + 3\triangle_0 \frac{D_0}{2t} \tag{2}$$

$$P_{el} = \frac{2E}{1-\nu^2}\left(\frac{t}{D_0}\right)^3 \tag{3}$$

$$P_p = 2\sigma_y \frac{t}{D_0} \tag{4}$$

where, P_{el} is the elastic instability, E is the elastic modulus, υ is Poisson's ratio, D_0 is the average diameters, t is the thickness of the pipe and P_p is the plastic instability. Considering the above equations, the collapse strength of a pipe with initial imperfections can be expressed as follows:

$$P_c = \frac{1}{2}\left\{(P_p + \mu P_{el}) - \left[(P_p + \mu P_{el})^2 - 4P_p P_{el}\right]^{1/2}\right\} \tag{5}$$

This equation represents a thin-walled pipe under linear elastic buckling and cannot be directly applied to a thick-walled pipe with nonlinear inelastic buckling. Equation (5) cannot accurately predict the collapse strength of thick-walled pipe. However, DNV-OS-F101, which is commonly used design standard for offshore steel pipe, is based on this classical design formula. Therefore, the collapse strength of a thick-walled pipe by DNV-OS-F101 is quite different from the actual collapse strength of the steel pipe.

Bastola (2014) performed parametric study of 132 cases using 2D and 3D nonlinear Finite Element Analysis (FEA) and pointed out the limitations of DNV-OS-F101. The variables are used as follows: the diameter to wall thickness (D/t) ratios, ovality, eccentricity, material properties and residual stresses in the hoop and longitudinal directions. Figure 3 and Figure 4 plot the collapse strength from FEA and DNV-OS-F101 against the D/t ratios for steel pipe using API X65 and API X70.

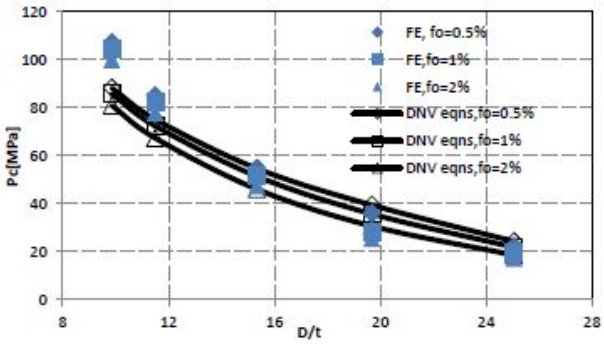

Figure 3 Comparison of Collapse Strength from FEA and DNV-OS-F101 for API X65 (Bastola, 2014)

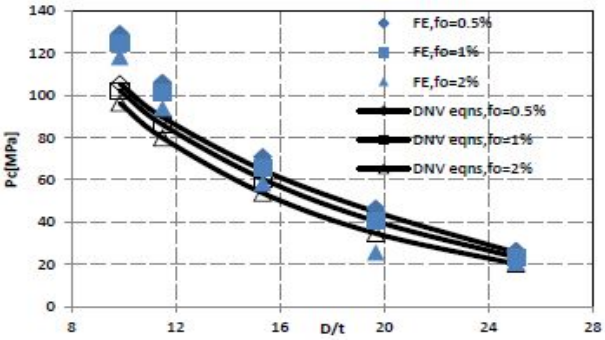

Figure 4 Comparison of Collapse Strength from FEA and DNV-OS-F101 for API X70 (Bastola, 2014)

From both figures, it is evidence that DNV-OS-F101 analysis based on the classical design formula evaluates the collapse strength as conservative for a thick-walled pipe with D/t ratios below 15. Also, Bastola (2014) performed a comparison of collapse strength for various residual stresses. Figure 5 plots the normalized collapse strength against the corresponding residual stress.

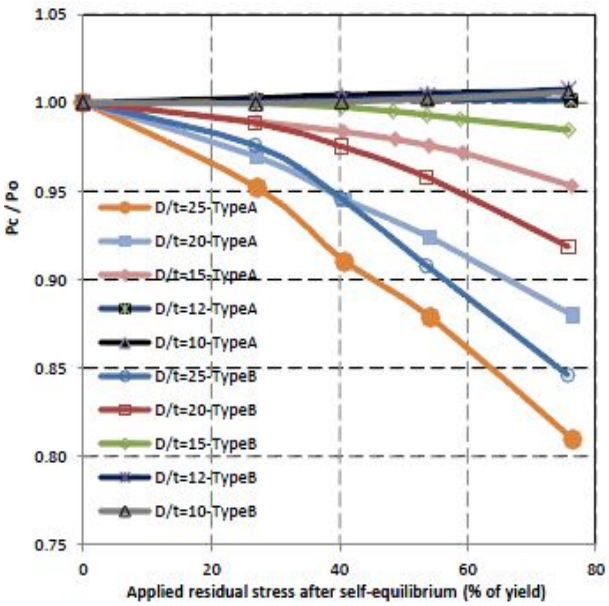

Figure 5 Effects of Residual Stress in the Hoop Direction on Normalized Collapse Strength (Bastola, 2014)

At this figure, TypeA indicates that tensile stress was applied at the outer surface of the pipe, and TypeB indicates that compressive stress was applied at the outer surface of the pipe. It is evidence that conservative assessment under tensile stress at the outer surface of pipe, and it can also be seen that the residual stress in the hoop direction has a decreasing

effects on the normalized collapse strength. However, there is not affected of residual stress in the hoop direction when the D/t ratios is less than 15.

The results of the analysis of eccentricity are shown in Figure 6. The collapse strength of the steel pipe with a D/t ratios of 19.69 decreased by 2.5%, whereas that with a D/t ratios of 9.86 decreased by only 1.35%. This suggested that eccentricity had only a minimal effect on the collapse strength of the steel pipe.

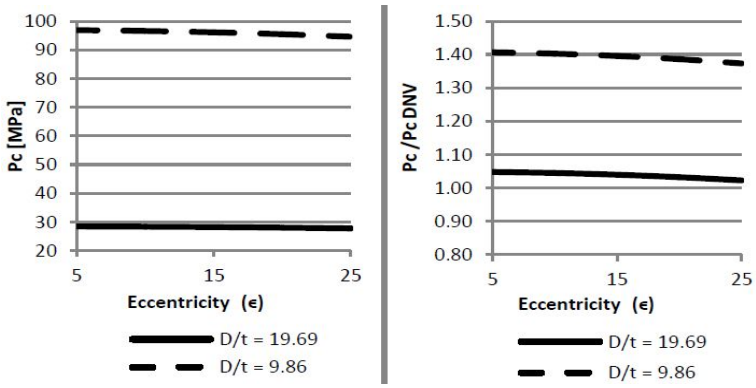

Figure 6 Effect of Eccentricity on Collapse Strength (Bastola, 2014)

Bastola (2014) demonstrated the necessity to optimized collapse strength evaluation equation to thick-walled pipes, because DNV-OS-F101 evaluates the collapse strength conservatively at D/t ratios below 15. In this case, the eccentricity or residual stress does not necessary to consider.

Tong (2014) pointed out the limitations of the collapse strength evaluation equation based on the classical design formula. Tong (2014) performed regression analysis in a parametric study of 441 finite element models of thick-walled pipe. The collapse strength was normalized by the

plastic instability P_p, and Tong's proposed equation is as follows:

$$\frac{P_{cr}}{P_p} = f\left(\frac{D}{t}, \frac{\sigma_y}{E}, imp\right) \tag{6}$$

$$f_0 = \frac{2(D_{\max} - D_{\min})}{D_{\max} + D_{\min}} \tag{7}$$

$$\frac{P_{cr}}{P_p} = a\left(\frac{D}{t}\right)^b \left(\frac{\sigma_y}{E}\right)^c + d\left(\frac{D}{t}\right)^e f_0^f \left(\frac{\sigma_y}{E}\right)^g \tag{8}$$

Table 1 Values of the Constants to be Used in the Proposed Equation (Tong, 2014)

Constants	a	b	c	d	e	f	g
Values	-1.478	0.611	0.379	2.436	-0.094	-0.047	0.049

where, *imp* is the value representing the imperfection amplitude, and f_0 is the initial imperfection. The accuracy of this collapse strength evaluation equation was verified by other researchers. In Figure 7, the collapse strength of thick-walled pipes is given. A comparison of the collapse strength derived from FEA and that from the proposed equation shows a maximum error of 10.5%.

However, the these researches have limitations. First, there is a lack of analysis about the behavior of thick-walled pipes under external pressure. A more exact comparison between thick-walled and thin-walled pipes is required. Second, it cannot reflect the changes in the collapse strength that can be achieved by changing the hardening parameter. The variety of

material models with different hardening parameters are given in Figure 8, and the results of collapse strength analysis using these material models in Figure 9, respectively. It can be seen that large in the collapse strength exist, especially at D/t ratios less than 15. These hardening parameters should be reflected in the collapse strength equation for thick-walled pipe.

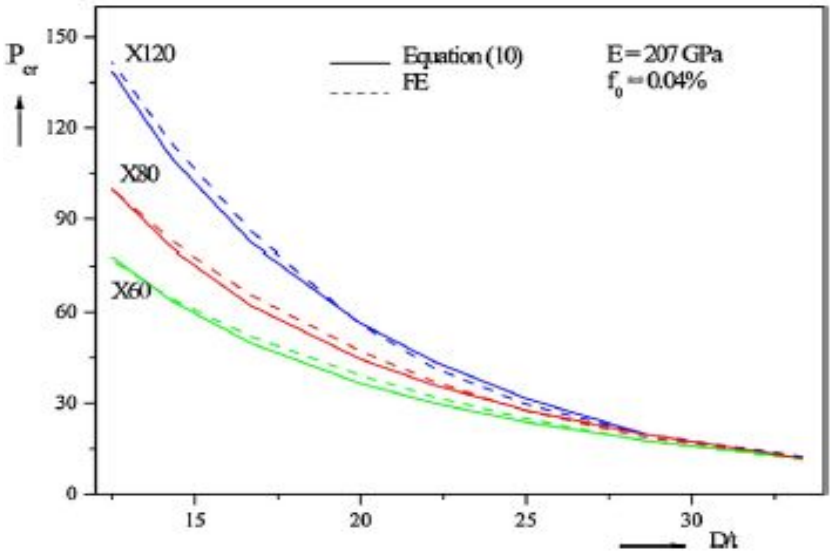

Figure 7 Collapse Strength at Different D/t Ratios and Steel Grades (Tong, 2014)

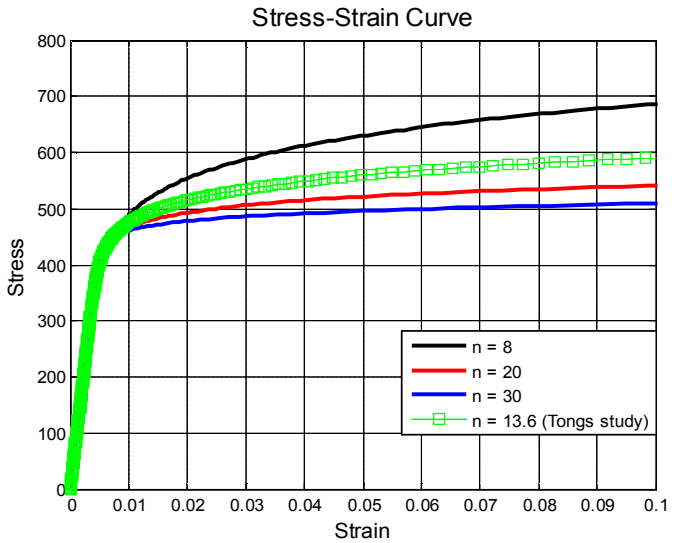

Figure 8 Comparison of Material Models at Different Hardening Parameters

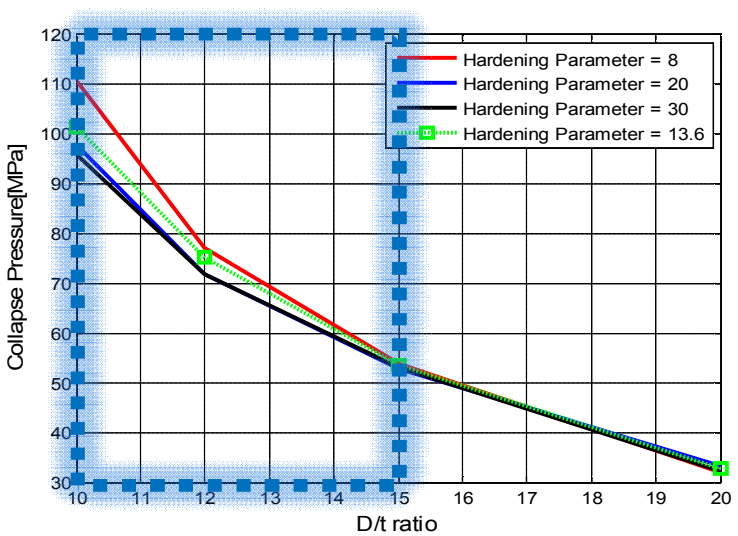

Figure 9 Comparison of Collapse Strength at Different Hardening Parameters

1.2 Research Objectives and Contents

In this research, the failure modes in thick-walled and thin-walled pipe were compared. The failure mode of thick-walled pipes is associated with post-buckling behavior and this was confirmed using FEA. A total of 360 cases were carried out, 3D nonlinear FEA, to provide a regression of the prediction equation for the collapse strength of a thick-walled pipe. Using this equation, the effect of key parameters on the collapse strength of thick-walled pipe was then examined.

In chapter 2, the current design standards used to determine the collapse strength are described. DNV-OS-F101, which is commonly used for offshore steel pipes, is based on linear elastic buckling in thin-walled pipe. However, it has limited power to accurately predict the collapse strength. It is therefore necessary to analyze different failure modes of thick-walled pipe.

In chapter 3, describes the failure mode of thick-walled pipe, which is associated with post-buckling behavior attributable to the greater strength of thick-walled pipe. The exact degree of strength enhancement is determined by the materials used and by geometric nonlinear properties. The analysis therefore considers the theoretical background and is conducted using 3D nonlinear FEA.

In chapter 4, the procedure for determining the collapse strength of a thick-walled pipe is described. A parametric study was performed using regression analysis. The form of model expression used in the regression analysis was determined by sensitivity analysis of the results of the

parametric study. The regression analysis was performed using the nonlinear statistical tools of in SPSS 23.

In chapter 5, conclusion of this research based on the contents mentioned above described.

2 Current Collapse Design Concepts

2.1 Local Buckling and Collapse

This section will look at the local buckling and collapse by external pressure. Also, the behavior of the actual steel pipe will be examined according to them.

The offshore steel pipe has inevitably distortion of cross-section and eccentricity, because it is made through mechanical manufacturing process. The initial imperfections of cross-section such as ovality and eccentricity are caused of the local buckling. Therefore, the main limit state of offshore steel pipe is collapse by local buckling, because it is vulnerable to external pressure, particularly during the construction phase. According to the DNV-OS-F101, as a commonly used design standard for offshore steel pipe, the local buckling is defined as buckling mode confined to a short length of the pipeline causing gross changes of the cross section; collapse.

Figure 8 shows the collapsed state of the steel pipe and Figure 9 shows the collapsed state of cross-section of the steel pipe, respectively. The local buckling is caused of propagation buckling. The propagation buckling is means that distortion of the cross-section transmits in longitudinal direction of steel pipe. The propagation buckling can provoke to increasing pressure of specific section of steel pipe and it is a big risk to safety. Thus, the exact assessment of local buckling limit state should be carried out during the

design phase.

when assessing the local buckling limit state, it is important problem that some moment is local buckling. In general, it is assumed that the local buckling occurred in steel pipe when the displacement is generated to infinity without further load increase. Accordingly, the maximum load is the peak attained in load-displacement curve, which will be the load used to defined the collapse strength of the steel pipe. It is shown in Figure 10. The definition of collapse strength holds regardless of thickness of steel pipe in this research.

The collapse strength which will be maximum load in load-displacement curve is evaluated by arc-length method. Because existing methods such as load and displacement control can not be obtained the exact solution in case of the load decrease. However, the arc-length method finds a exact load-displacement curve even though the load decreases. Because this method finds a equilibrium point using step length concepts.

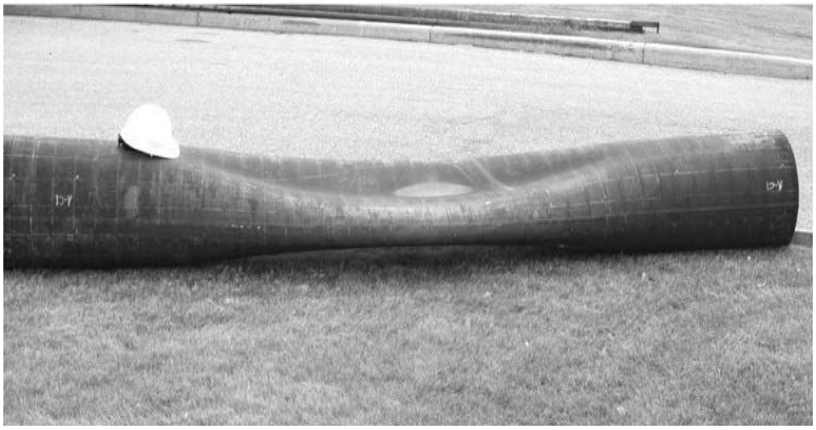

Figure 10 Collapsed State of Steel Pipe (Kyriakides, 2007)

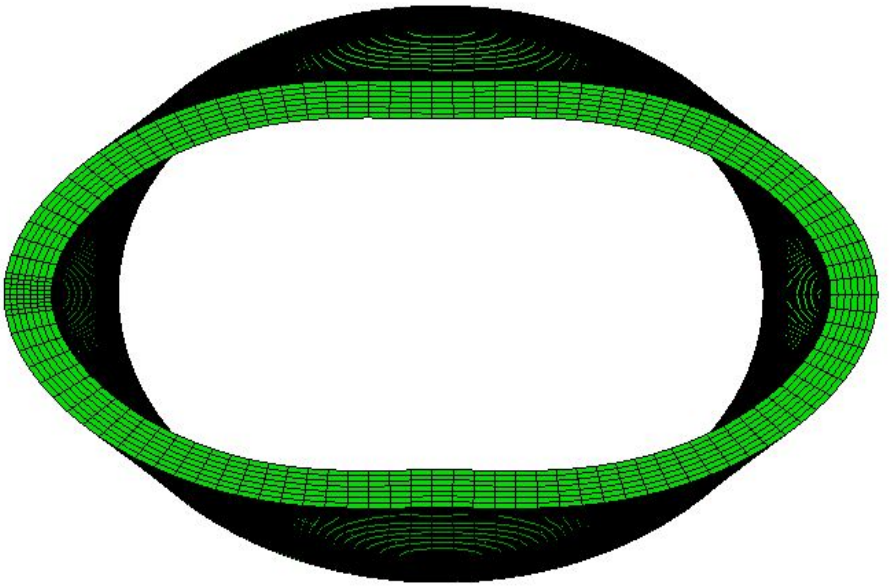

Figure 11 Collapsed State of Cross-Section of Steel Pipe

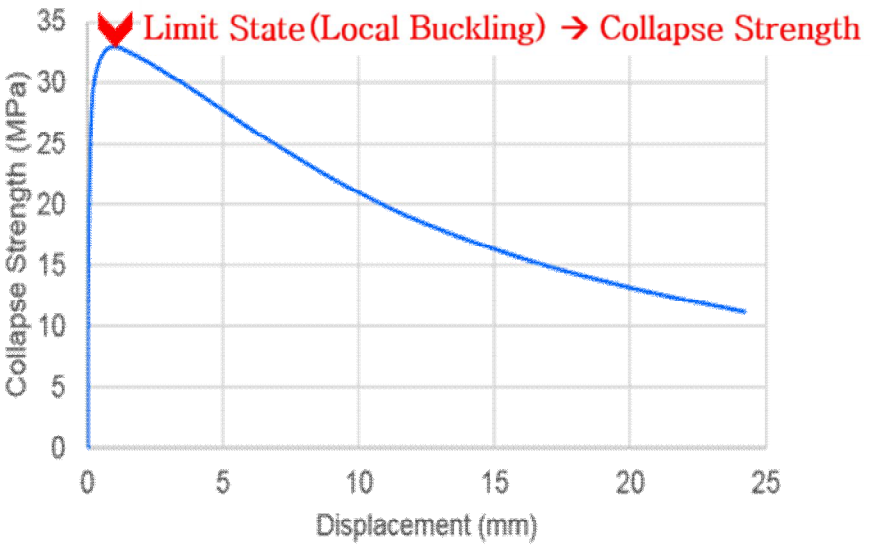

Figure 12 Definition of Collapse Strength on Load-Displacement Curve

2.2 Elastic Buckling

The buckling modes of steel pipe can be divided into elastic buckling and inelastic buckling according to characteristic of failure. This section will look at the elastic buckling which is basis of current design standard, especially.

The steel pipe has a initial imperfection such as ovality and eccentricity due to mechanical manufacturing process. These are causative of collapse by local buckling under external pressure. The local buckling is occurred in direction of distortion of the cross-section.

According to the mechanics of local buckling and collapse of pipe under external pressure, the collapse strength of steel pipe with elastic buckling is evaluated by the combination of elastic instability and plastic instability. This equation is expressed by Equation (5).

When the collapse strength of steel pipe with elastic buckling is evaluated, some assumptions are required. First, All stress of the steel pipe caused by external pressure concentrated into four regions. Suppose a cross section of the steel pipe to deform shown in Figure 13. If the local buckling occurs, two opposite regions move together until they meet and the other move in the opposite direction. Also, at this moment, the collapse strength is not affected by the stress distribution of the others region of steel pipe. This mode of collapse assumed in analysis.

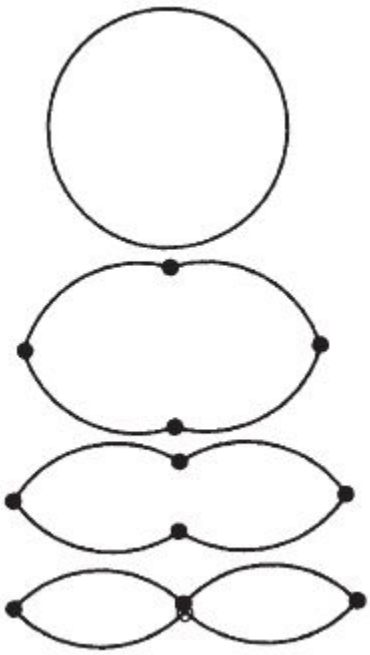

Figure 13 Mode of Collapse Assumed in Elastic Buckling Analysis (Palmer, 1975)

Second, the plastic range of material property is not considered in buckling analysis. Accordingly, the local buckling limit state occurs when the stress on concentrated regions reaches the yield stress. Suppose a stress distribution in the thickness direction shown in Figure 14 and Figure 15 is shown that material property used for buckling analysis. However, this assumptions do not consider to the post-buckling behavior requiring to nonlinear analysis, therefore an updated prediction equation of collapse strength of thick-walled pipe with inelastic buckling is necessary including to post-buckling strength. The post-buckling behavior is influenced by material and geometric nonlinear property. For a detailed description of these are given in Section 3.1 and 3.2.

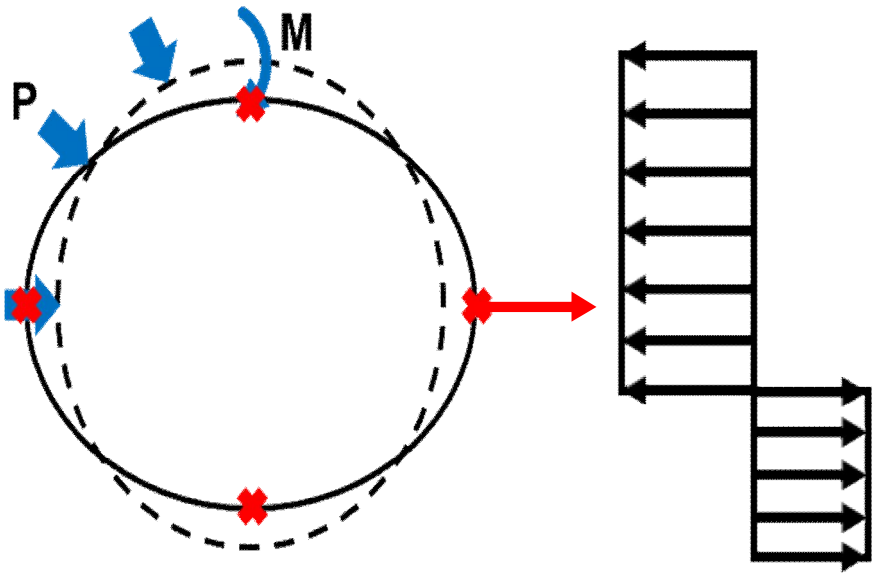

Figure 14 Stress Distribution at Moment of Local Buckling

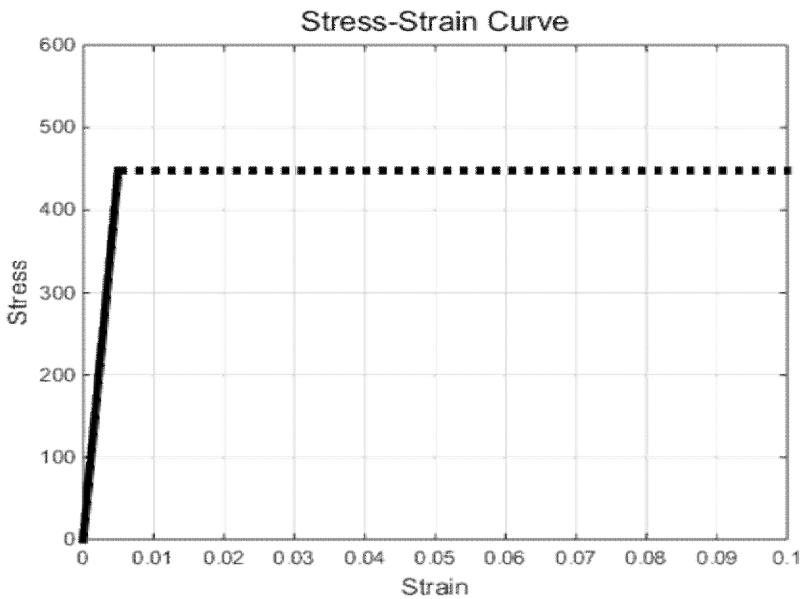

Figure 15 Material Model used for Analytic Buckling Analysis

2.3 DNV Offshore Standard

DNV-OS-F101 is one of the most commonly used standard for designing offshore steel pipe. It has assessed the safety of offshore steel pipe by limit state design method. The limit state can be divided into ultimate limit state, serviceability limit state, fatigue limit state and accidental limit state in this standard. The local buckling and collapse belong to the ultimate limit state.

The local buckling and collapse are defined by load and resistance factor design format.

$$P_e - P_{\min} \leq \frac{P_c(t)}{\gamma_m \gamma_{sc}} \tag{9}$$

where, P_e is the external pressure, P_{min} is the internal pressure, P_c is the collapse strength, Υ_m and Υ_{sc} are the resistance factors. In generally, the internal pressure is taken as zero for offshore steel pipe during the construction phase.

The evaluation of collapse strength by DNV-OS-F101 is based on the method originally proposed by Haagsma and Schaap's (1981). This equation of collapse strength is considered variables such as D/t ratios, ovality and material properties. However some properties are ignored such as plastic behavior and residual stress. The collapse strength is defined as follows:

$$P_c(t)^3 - P_{el}(t)P_c(t)^2 - \left(P_p(t)^2 + P_{el}(t)P_p(t)f_0\frac{D}{t}\right)P_c(t) + P_{el}(t)P_p(t)^2 = 0 \tag{10}$$

$$P_{el} = \frac{2E}{(1-\nu^2)}\left(\frac{t}{D}\right)^3 \tag{11}$$

$$P_p = 2\sigma_y \frac{t}{D}\alpha_{fab} \tag{12}$$

where, P_c is the collapse strength, P_{el} is the elastic instability, P_p is the plastic instability, f_0 is the ovality and α_{fab} is the fabrication factor. This factor is defined by manufacturing process. It is given in Table 2. Also, the range of D/t ratios is limited from 15 to 45.

Table 2 Maximum Fabrication Factor, α_{fab} (DNV, 2013)

Pipe	Seamless	UO & TRB & ERW	UOE
α_{fab}	1.00	0.93	0.85

In DNV-OS-F101, the collapse occurs when a compressive forces and bending moments in plane are increased to such an extent that plastic hinges are formed at the stress concentrated regions mentioned in Figure 14. The internal load condition in plane is shown at the Figure 16. Accordingly, the failure criteria is defined as follows:

$$\left(\frac{P_c(t)}{P_p(t)}\right)^2 + \frac{M_{\max}}{M_p} = 1 \tag{13}$$

where, M_p is the plastic moment and defined as follows:

$$M_p = \frac{\sigma_y t^2}{4} \tag{14}$$

$$M_{\max} = \frac{\sigma_y t^2}{4} \tag{15}$$

In Summary, DNV-OS-F101, as a commonly used design code for offshore steel pipe, includes the assumptions of elastic buckling which demonstrate in Section 2.2: (1) All stress of the steel pipe caused by external pressure concentrated into four regions. (2) The plastic range of material property is not considered in buckling analysis. Accordingly, the range of D/t ratios is limited, because the prediction of the collapse strength using DNV-OS-F101 is not accurate when D/t ratios is less than 15. Bastola (2014) pointed out these limitations. The current design standard of thick-walled pipe is performed depending on engineering decision and trial & error method. Therefore a further optimized prediction equation of the collapse strength is necessary for thick-walled pipe used for the design phase.

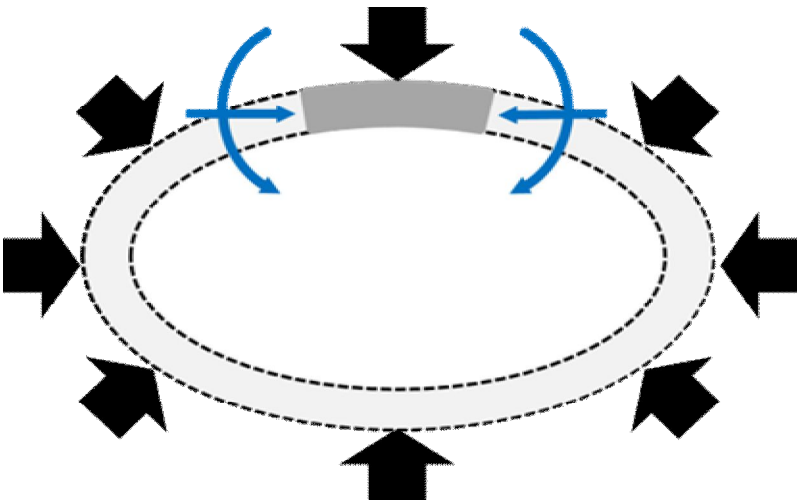

Figure 16 Compressive Forces and Bending Moments in Plane

3 Collapse of Thick-walled Pipe

The offshore steel pipe has been commonly used a range of the D/t ratios between 12.5 and 30. Also, it may become thicker because mining of resource in deep-water that has not been considered as an economical problem is increasing. However, DNV-OS-F101, as a widely used design standard for offshore steel pipe, limits the design when D/t ratios is less than 15. The design concepts of thick-walled pipe with D/t ratios below 15 are different from concepts of current design standard. In this section, the failure mode of thick-walled pipe is demonstrated by theoretical background and verified using 3D nonlinear FEA.

3.1 Post-Buckling Behavior

The buckling means that the structures such as column and pipe are suddenly bent by geometric shape when the load reaches certain magnitude. Under compression, the levels of analysis in load-displacement curve of structures are illustrated in Figure 17 and the levels of analysis are defined as follows. First, the 1st order elastic analysis represents conditions at service load very well. The elastic critical load where both the original and an alternative loading path become mathematically valid. It can be obtained from idealized elastic model of structures. The inelastic critical load is similar defined as elastic critical load. However, the possibility of actual inelastic material behavior is already considered in the analysis. In summary, the concepts of

the 1st order elastic analysis is used in current design standards. Second, the 2nd order elastic analysis means that the geometric nonlinearity. It is powerful in representation of destabillizing influence such as P-△ effect. However, it does not include material nonlinearity. Third, the 1st order inelastic analysis means that the material nonlinearity. The equilibrium equation is written in terms of the geometry of the undeformed structures. This level of analysis gives excellent results by the simple plastic limit load, if the destabillizing effect of finite displacements is relatively insignificant. However, it does not include geometric nonlinearity. Finally, the 2nd order inelastic analysis means that the material and geometric nonlinearity. This analysis can accurately simulate actual behavior of structures and calculate the inelastic stability limit. The material and geometric nonlinearity is detailedly demonstrated in Section 3.2 and Section 3.3, respectively.

The actual structures with 2nd order inelastic behavior can be collapsed at the limit point which exceeds a bifurcation point. It is illustrated in Figure 18. It mainly occurs in thick-walled pipe. After buckling, the thick-walled pipe does not reach a limit state immediately. Because there is resistance force by material and geometric nonlinearity. It is called as the post-buckling behavior. Then, the collapse strength is defined as peak point in Figure 18. The nonlinear analysis is needed to consider strength enhancement which is generated by the post-buckling behavior after bifurcation point. It is illustrated in Figure 19. If the post-buckling is not considered, the exact collapse strength of thick-walled pipe is not predicted. The exact post-buckling analysis is difficult using existing analytic method. Accordingly, the nonlinear FEA is used for considering to post-buckling behavior.

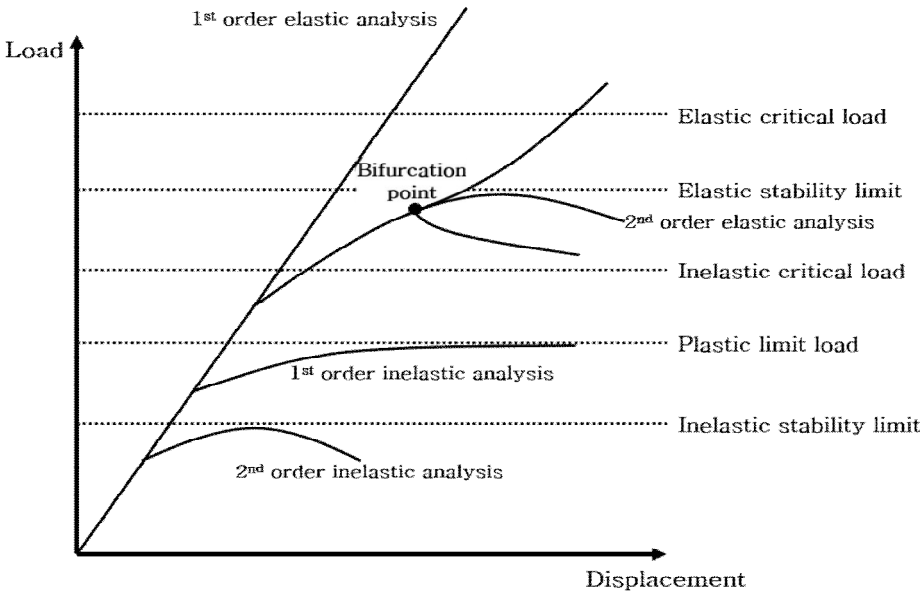

Figure 17 Levels of Analysis in the Load-Displacement Curve

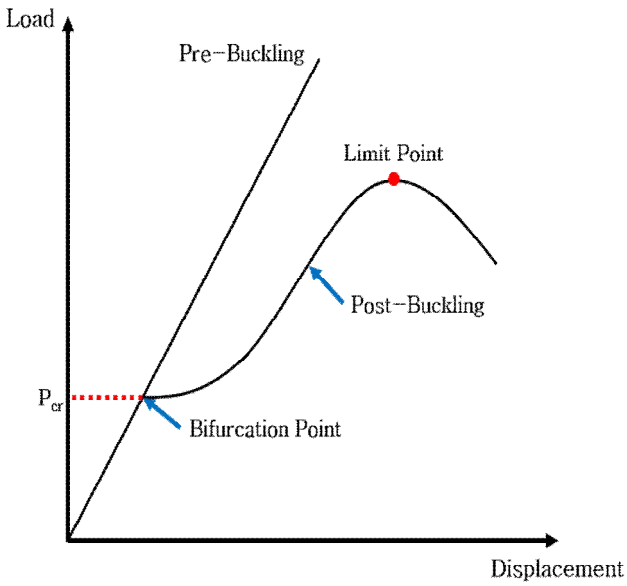

Figure 18 Limit Point According to the Post-Buckling Behavior

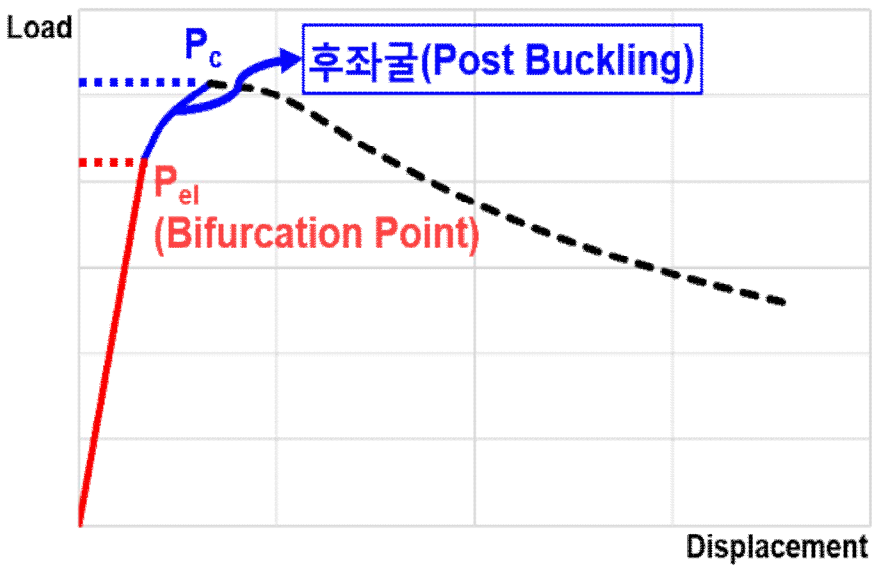

Figure 19 Strength Enhancement due to the Post-Buckling Behavior

3.2 Nonlinear Properties

The failure mode of thick-walled pipe differs from that of thin-walled pipe due to the post-buckling behavior. In this section, the nonlinear properties associated with post-buckling behavior are demonstrated. It should be considered in the buckling analysis of thick-walled pipe.

3.2.1 Material Nonlinearity

In generally, the material nonlinearity means that plastic behavior of materials in steel structures. The steel structures behave linearly up to yield

point on the material model. However, the permanent deformation remains when the external load is applied beyond the yield point. Some plastic deformation is permitted when the limit state design can be performed. It is called the plastic design method. In this design method, plastic deformation is allowed, if it is not critical. The plastic design method has several advantages over the elastic design method. It is more efficient and economical. Futhermore, it can realistically describe actual behavior of steel structures. Because the plastic design method fully considers the important property such as ductility.

When the structural analysis considering to material nonlinearity is performed, the collapse strength is different according to material models, respectively. The material models such as Ramberg-Osgood, Bilinear, Perfectly plastic model are illustrated in Figure 20. These material models have same yield stress. However, it each made a different collapse strength. Because the plastic behaviors are different in the same strain. The material nonlinearity is occurred in the thick-walled pipe, especially. The D/t ratios to buckling stress curve is shown in Figure 21. In case of current design standard is based on elastic buckling that is not considered the plastic range of material, the yield stress is defined as a buckling stress even if D/t ratios is small. However, the local buckling can be occurred in stress greater than yield stress, if the steel pipe has the D/t ratios less than the critical D/t ratios. The buckling stress is determined by material models and D/t ratios. Therefore, the buckling analysis considering to material nonlinearity is requisite for design of thick-walled pipe.

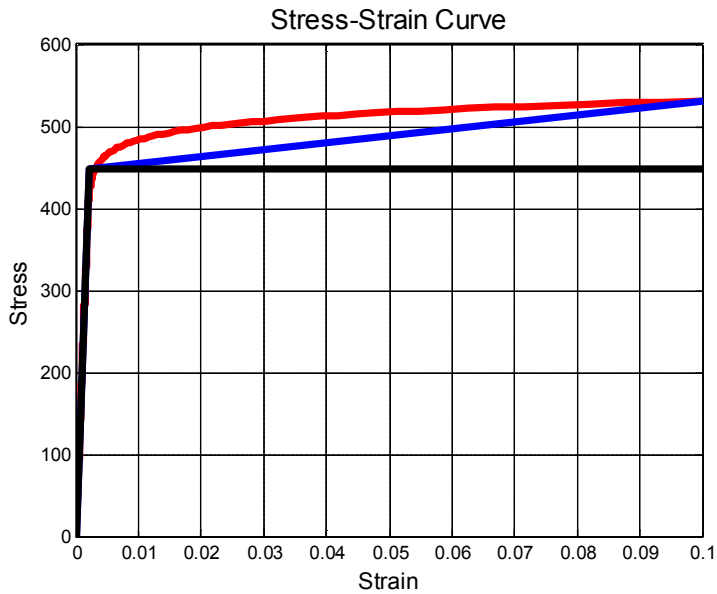

Figure 20 Various Stress-Strain Curves According to Plastic Behavior

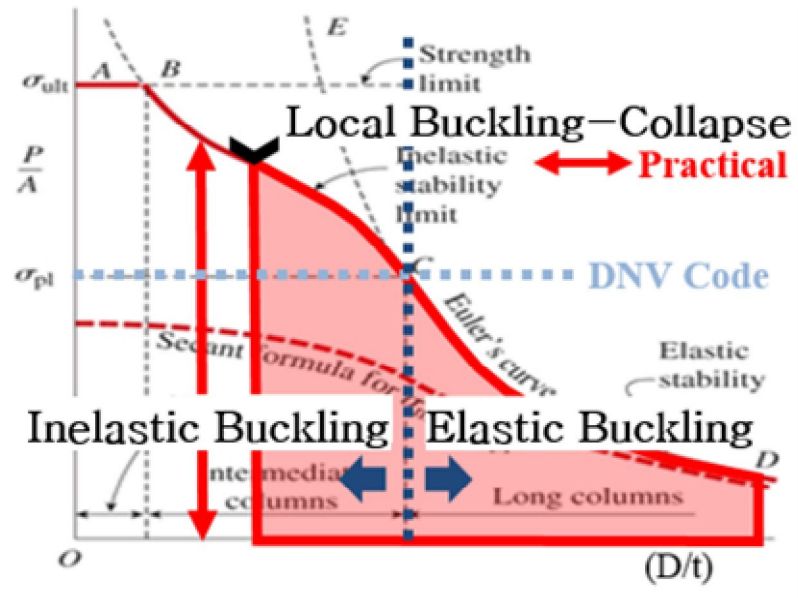

Figure 21 D/t ratios to Buckling Stress Curve

3.2.2 Geometric Nonlinearity

In theory of elasticity, the stress is proportional to elastic modulus and strain.

$$\sigma = E \cdot \epsilon \tag{16}$$

However, this definition can be applied to only small strain occurs in the structure. In the case of small strain, the deformation of structure can be assumed as follows:

$$\sin\theta \cong \theta \tag{17}$$

On the basis of these properties, all stress of the steel pipe caused by external pressure concentrated into four regions in the buckling analysis of current design standard. However, this assumption is not appropriate for buckling analysis of thick-walled pipe with large deformation. In case of large deformation, the assumption of Equation (17) does not satisfy. Also, the stress distribution of cross-section is not concentrated into four regions. The moment of the other regions increases and the resistance force appears. Accordingly, the collapse strength can be increased. It is the effect of geometric nonlinearity.

Therefore, the buckling analysis of thick-walled pipe should be tracking load and boundary conditions which changes every increments.

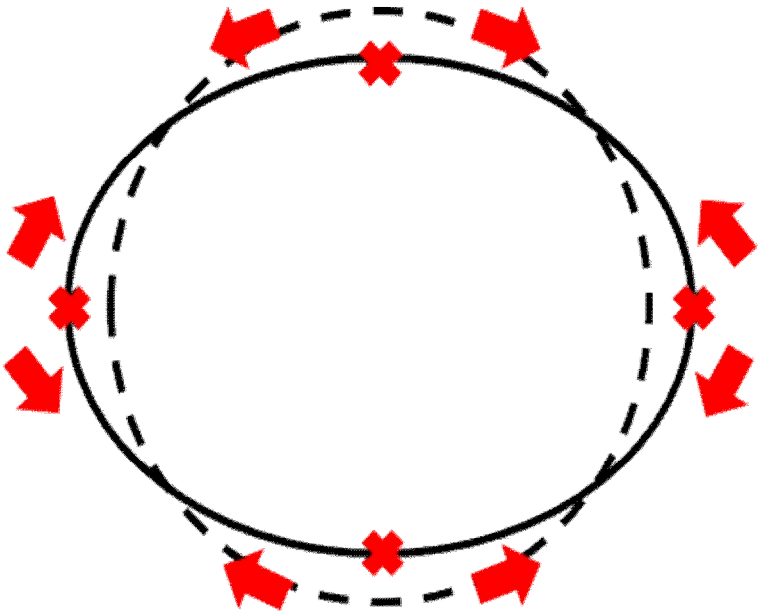

Figure 22 Stress Distribution around the Whole Cross-Section

3.3 Finite Element Approach

In Section 3.2, theoretical backgrounds of nonlinear properties which are related to post-buckling were demonstrated. In this section, the comparison of failure mode between thick-walled and thin-walled pipe is verified using FEA. The nonlinear analysis including material and geometric properties is performed because of description of the post-buckling behavior.

3.3.1 Configuration of Finite Element Model

In this research, the ABAQUS 6.10 standard platform is used for evaluating

the collapse strength of steel pipes. It is a widely used for nonlinear analysis and has high accuracy. In analysis, there is only considered the external pressure in normal direction of outer surface in order to determine of the limit state under the construction phase. The offshore steel pipe is modeled as 3D half model and the longitudinal symmetry is used in boundary condition. Also, the axial motion is allowed. Because it is assumed that each axial strain of cross-section is different in case of the infinite offshore steel pipe. In Figure 23, a dotted line means that fixed condition and a solid line means that free condition. The 8-noded brick element with reduced integral (C3D8R) is used for FEA. Each node has six degree of freedom and it is commonly used for large deformation analysis. The Ramberg-Osgood model is used in material model. It is similar to mechanical behavior of actual steel pipe (Ramberg, 1943). This material model is configured as Equation (18). The hardening parameter is defined as n.

$$\epsilon = \frac{\sigma}{E}\left[1 + \frac{3}{7}\left(\frac{\sigma}{\sigma_y}\right)^{n-1}\right] \tag{18}$$

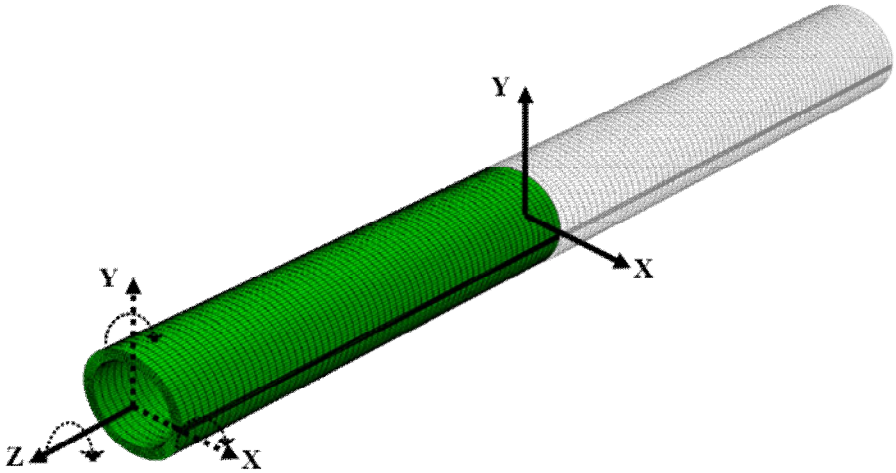

Figure 23 Boundary Condition of 3D Half Model

3.3.2 **Accuracy Verification**

The accuracy of the FEA model was verified by the analytic and experimental results from other researcher. First, the element stress of radial and hoop direction compared with analytic results. The element stress is defined as the following equation:

$$\sigma_r = Radial\ stress = -P_0/2 \tag{19}$$

$$\sigma_\theta = Hoop\ stress = -P_0 D_0/2t \tag{20}$$

where, P_0 is the external pressure, D_0 is the diameter and t is the thickness of cross-section. The comparison between FE results and analytic method are illustrated in Figure 24 and Figure 25, respectively.

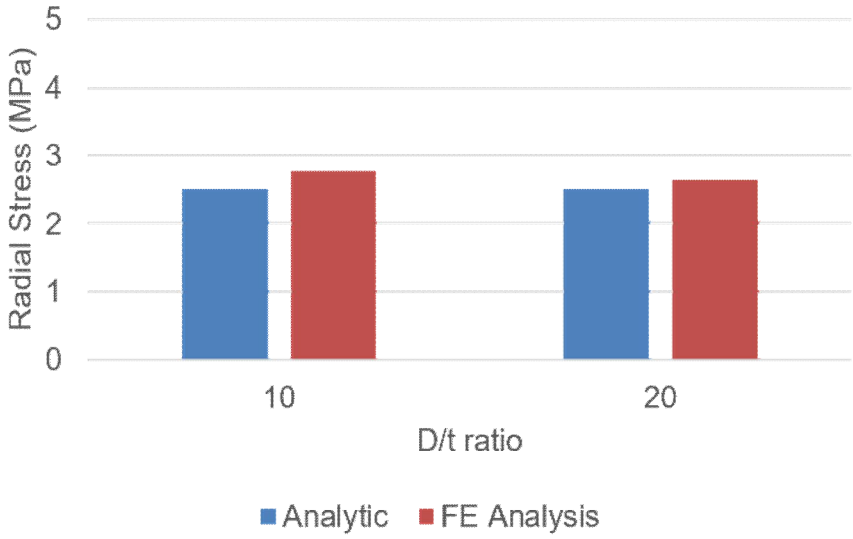

Figure 24 Comparison between Analytic and FE results in Radial Stress

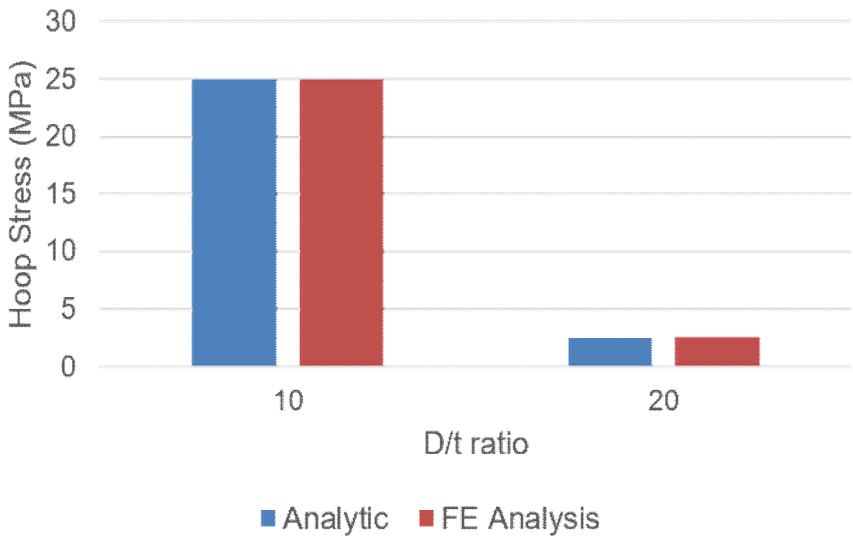

Figure 25 Comparison between Analytic and FE results in Hoop Stress

Second, The collapse strength compared to experimental results. The collapse test was performed by Kyriakides (2007). The specification of steel pipe and comparison results are shown in Table 3 and Figure 26, respectively. The tolerance was occurred as a result of comparison with analytic and experimental results. Therefore, the configured finite element model can be represented a behavior of offshore steel pipe under the construction phase to show well.

Table 3 Specification of Steel Pipe in Accuracy Verification (Kyriakides, 2007)

Constants	D/t ratios	Ovality (%)	Yield Stress (MPa)
Case 1	17.75	0.37	414.37
Case 2	17.92	0.34	477.46
Case 3	17.64	0.22	375.76
Case 4	17.79	0.59	421.61
Case 5	16	0.4	435.75

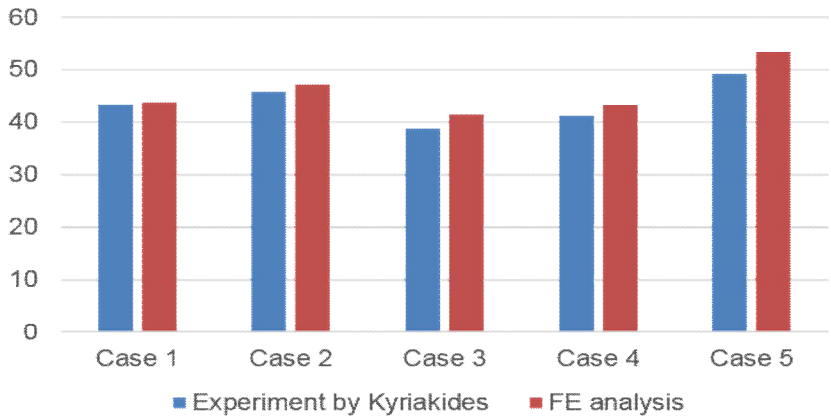

Figure 26 Comparison between FE and Experimental Results

3.3.3 **Validation of Convergence**

The mesh study was performed in order to validate a convergence: number of elements in the radial direction - 5, 7, 9 and number of elements in the axial direction - 100, 130, 160. The experimental result of Kyriakides (2007) is regarded as a exact solution. The results of validation of convergence are shown in Figure 27. The difference between analysis time occurred up to five according to number of elements. Therefore, number of elements are defined as 7 and 130 considering to efficiency and accuracy.

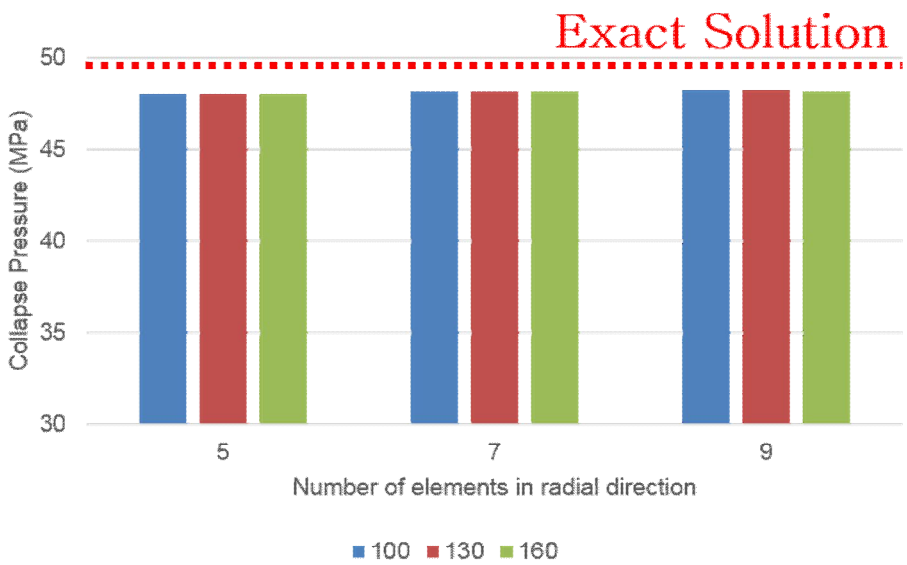

Figure 27 Influence of Number of Elements in Radial and Axial Direction

3.3.4 **Verification using Finite Element Analysis**

The comparison of failure mode between thick-walled and thin-walled pipe is performed using qualified FEA model. The range of key parameters is

defined by actual steel pipe's specification. It is given in Table 4.

Table 4 Range of Key Parameters used for Comparison of Failure Mode

Constants	D/t ratios	Ovality (%)	Yield / Tensile stress (MPa)
Thick-walled	10	0.5	448 / 630
Thin-walled	30	0.5	448 / 630

This table shows the thick-walled pipe and the thin-walled pipe in case of D/t ratios in 10 and 30 with same conditions. The Ramberg-Osgood model is used for material model. The stress distribution of cross-section for each D/t ratios is shown in Figure 28. Also, Figure 29 and Figure 30 show that the load-displacement curve and a moment with collapse on material models, respectively. In these figures, STEP 2 indicates the local buckling limit state, and the others indicate the front and back increment. In case of D/t ratios = 30, the failure mode is similar to current design standard's failure mode. All stress of the steel pipe caused by external pressure concentrated into four regions. Also, the local buckling is occurred in elastic range of material model. This failure mode is similar to elastic buckling of mechanics of buckling and collapse of pipes. Therefore, the collapse strength by FEA and DNV-OS-F101 which is based on mechanics of buckling are similar. However, in case of D/t ratios = 10, the collapse took on a new aspect. The stress distribution spreads around the whole cross-section. By distributing the external pressure in a wide cross-section, it can endure greater the collapse strength than stress concentrate model. Also, the local buckling is occurred in plastic range of material model. It is the effect of nonlinear analysis. The collapse strength by FEA and DNV-OS-F101 are different with realistic

analysis.

Using 3D nonlinear FEA, The assumption that the collapse strength of thick-walled pipe is determined by the post-buckling behavior is verified. Therefore, when evaluating the collapse strength of the thick-walled pipe, the limitation of analytic method should be compensated by nonlinear analysis.

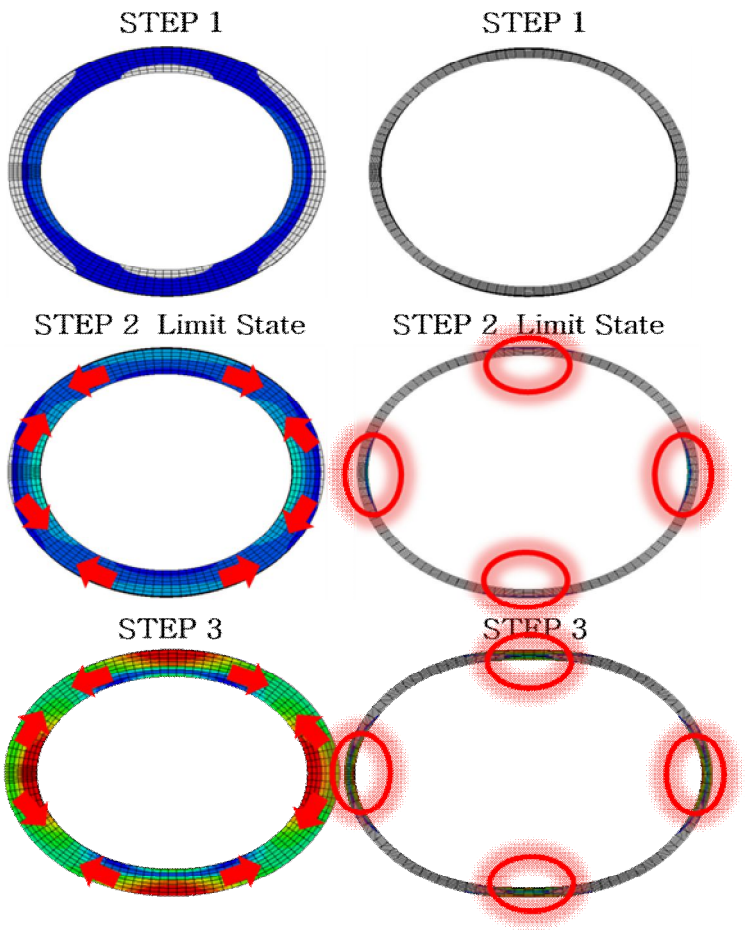

Figure 28 Stress Distribution of Cross-Section for Each D/t ratios (D/t ratios = 10, 30)

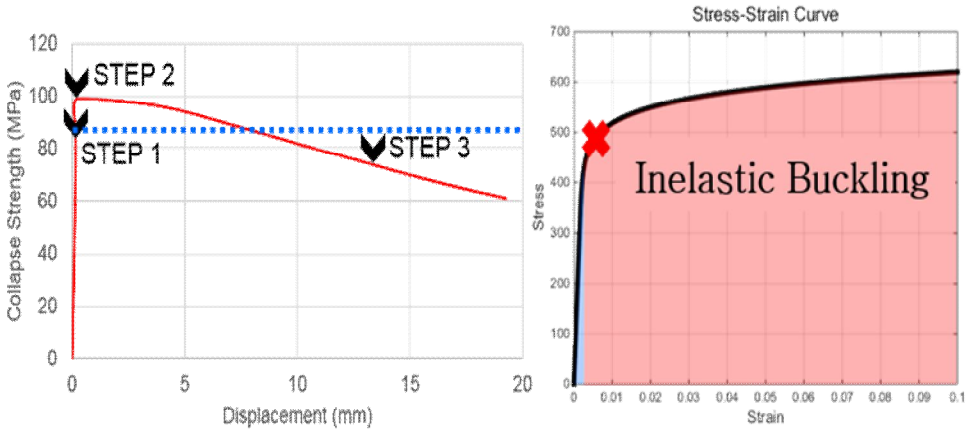

Figure 29 Load-Displacement Curve and Moment with Collapse on Material Model (D/t ratios = 10)

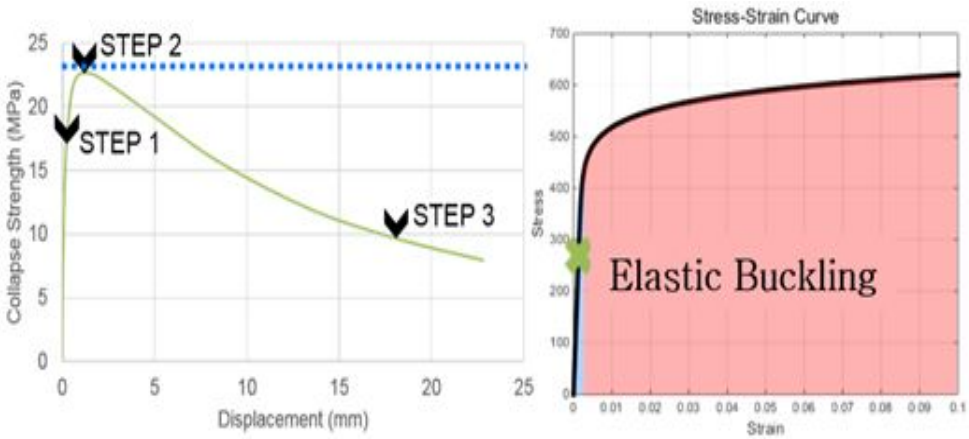

Figure 30 Load-Displacement Curve and Moment with Collapse on Material Model (D/t ratios = 30)

4 Prediction of Collapse Strength for Thick-walled Pipe

4.1 Parametric Study

4.1.1 Range of Parameters

The parametric study was performed in order to accurately predict the collapse strength of thick-walled pipe and the prediction equation was defined by regression analysis of the results.

The definition and range of key parameters are important in the parametric study. The previous studies found that various parameters such as D/t ratios, ovality, eccentricity, material model and residual stress affects to the collapse strength of steel pipe. However, the collapse strength of thick-walled pipe is not influenced by eccentricity and residual stress (Bastola, 2014).

At this research, an aim is the collapse strength of thick-walled pipe with D/t ratios below 15. Because the collapse strength of steel pipe with D/t ratios above 15 can be accurately predicted through current design standard. Accordingly, the eccentricity and residual stress are not considered as key parameters.

The assumption that the collapse strength of thick-walled pipe is determined by the post-buckling behavior was confirmed in Section 3. The post-buckling behavior is influenced by material and geometric nonlinearity. Therefore, the material model which is similar to mechanical behavior of

actual steel pipe should be used and considered variability of plastic range. The difference of collapse strength which was determined by variability of plastic range is shown in Figure 8 and Figure 9. Thus, the Ramberg-Osgood model which can represent behavior of actual steel pipe is used. Also, the variability of plastic range is considered by yield stress and hardening parameters.

The other key parameters are D/t ratios and ovality. The effect of these on the collapse strength can be expressed by analytic equation. First, the effect of D/t ratios is showed as follows. In Figure 31, half of the pipe is shown. The solid line indicates the initial shape and the dotted line indicates the deformation shape. It is assumed that symmetry. At this moment, the differential equation for the deflection curve of the pipe is defined as follows:

$$\frac{d^2w}{ds^2}+\frac{w}{R^2}=-\frac{M}{EI} \tag{21}$$

And, the bending moment of arbitrary cross-section is defined as follows:

$$M=M_0-qR(w_0-w) \tag{22}$$

where, w_0 is the radial displacement. Substituting Equation (22) in the Equation (21), we obtain the collapse strength. It is defined as follows:

$$q_{cr}=\frac{3EI}{R^3} \tag{23}$$

Substituting moment of inertia of rectangular cross-section in the Equation (23), the collapse strength can be expressed by D/t ratios.

$$I = \frac{bh^3}{12} \tag{24}$$

$$q_{cr} = \frac{Ebh^3}{4R^3} = \frac{Et^3}{4D^3} \tag{25}$$

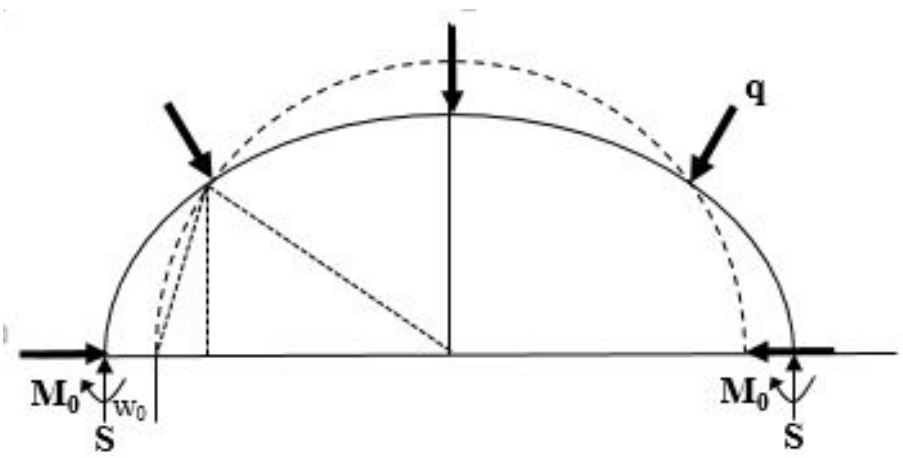

Figure 31 Free Body Diagram of Half of the Pipe under External Pressure (Timoshenko and Gere, 1961)

Second, the effect of ovality is expressed as follows. In Figure 32, the distorted cross-section which is occurred by external pressure is shown. The moment of inertia are different according to how distorted been based on any axis. The moment of inertia about the x-axis and y-axis are defined as follows:

$$I_x = \frac{\pi\{ab^3 - (a-t)(b-t)^3\}}{4} \tag{26}$$

$$I_y = \frac{\pi\{ba^3 - (b-t)(a-t)^3\}}{4} \tag{27}$$

If the pipe is distorted in the x-axis direction, I_y is bigger than I_x. Then the collapse strength is defined by I_x. Thus, the ovality which means distortion of the cross-section is important when the collapse strength determine.

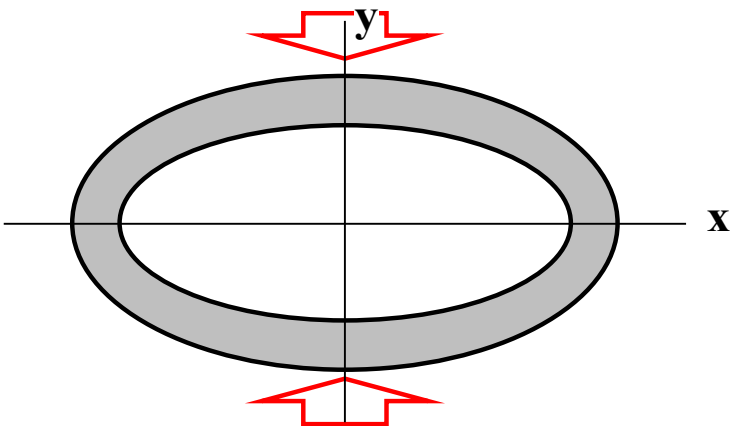

Figure 32 Distortion of Cross-Section by External Pressure

As a result, D/t ratios, ovality, yield stress and hardening parameters are defined as a key parameters. The range of key parameters are shown in Table 5. A total of 360 cases have been studied covering thick-walled pipe with D/tr ratios below 15.

Table 5 Range of Key Parameters used for Parametric Study

Constants	D/t ratios
D/t ratios	10, 11, 12, 13, 14, 15
Ovality	0.001, 0.005, 0.01, 0.015, 0.02
Yield Stress (MPa)	API X65(448) / X70(483) / X80(552)
Hardening Parameter	8, 14, 20, 30

The range of ovality are determined by previous research. It can be assumed less than 2% regardless of mechanical manufacturing process. The yield stress which commonly uses in actual industry is considered: API X65 / X70 / X80. The hardening parameters are determined by range of yield stress and tensile stress of API code. The range is shown in Table 6.

Table 6 Range of Yield and Tensile Stress used for Determination of Hardening Parameter (American Petroleum Institute, 2004)

	Yield Stress (MPa)		Tensile Stress (MPa)	
	Min	Max	Min	Max
X65	448	600	531	758
X70	483	621	565	758
X80	552	690	621	827

4.1.2 **Sensitivity Analysis**

The sensitivity analysis was performed to verify following: (1) the tendency of collapse strength by key parameters's variation (2) the form of key parameters in the prediction equation. The collapse strength decreased when D/t ratios, ovality and hardening parameter increased. Also, the collapse strength increased when yield stress increased. This tendency is similar in all analysis case. Based on this results, the key parameters in an exponential form are reflected in the prediction equation.

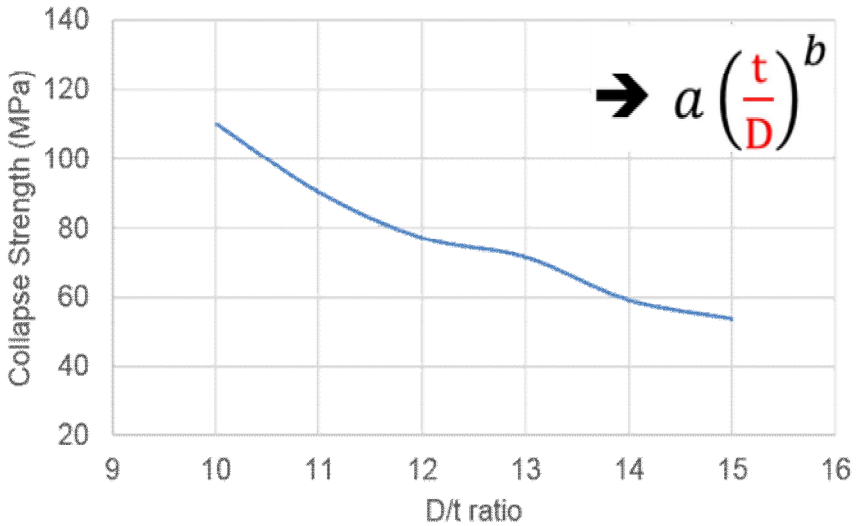

Figure 33 Tendency of Collapse Strength by D/t ratios

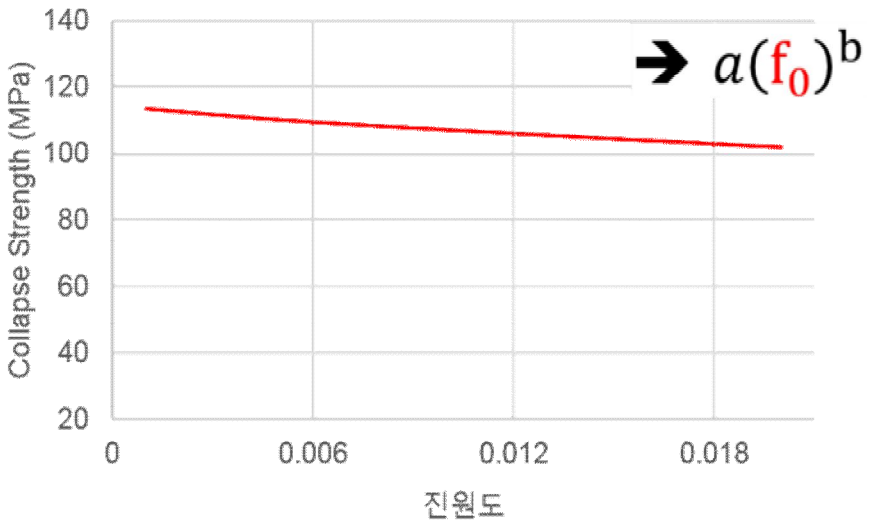

Figure 34 Tendency of Collapse Strength by Ovality

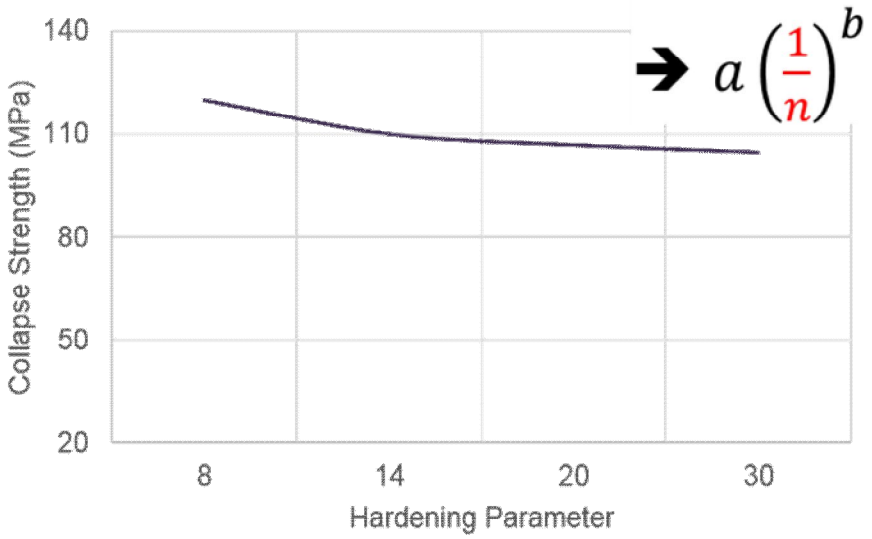

Figure 35 Tendency of Collapse Strength by Hardening Parameter

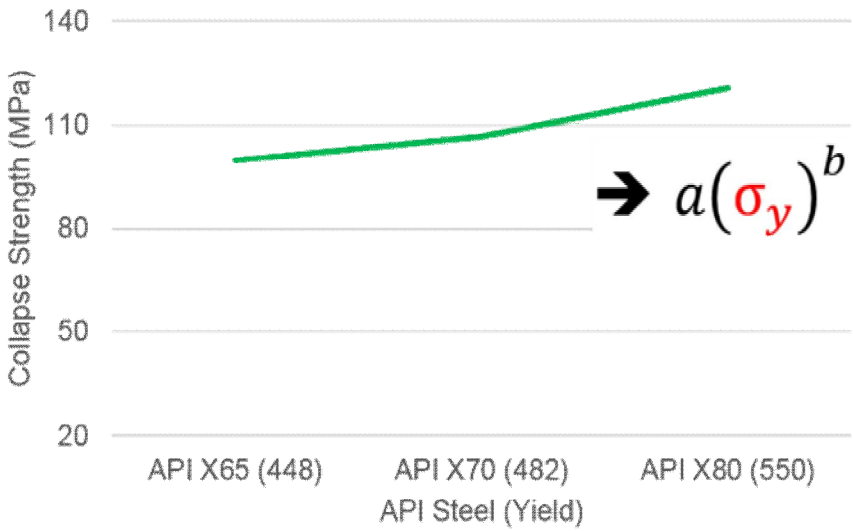

Figure 36 Tendency of Collapse Strength by Yield stress

4.2 Prediction Equation for Collapse Strength

In this section, the prediction equation was configured using results of parametric study. The procedure is defined as follows. First, an appropriate fundamental form of the equation was composed using results of sensitivity analysis. Afterwards, the regression analysis was performed using commercial statistics program. As a result, the exact collapse strength can be evaluated using this prediction equation.

4.2.1 Fundamental Form of the Equation

The prediction equation is based on original plastic buckling equation and Tong (2014)'s proposed equation. The original plastic buckling is defined as Equation (4). The prediction equation is composed of D/t ratios, ovality, yield stress and hardening parameter. Therefore, it is defined as follows:

$$P_{cr} = f(D/t\ ratios, f_0, \sigma_y, n) \tag{28}$$

$$P_{cr} = a \times \sigma_y^b \times \left(\frac{10t}{D}\right)^c + d \times \sigma_y^e \times \left(\frac{10t}{D}\right)^f \times f_0^g + h \times \sigma_y^i \times \left(\frac{10t}{D}\right)^j \times \left(\frac{1}{n}\right)^k \tag{29}$$

where, f_0 is the ovality and defined as follows:

$$f_0 = \frac{D_{\max} + D_{\min}}{D_{avg}} \tag{30}$$

The effect of hardening parameter is considered in order that limitation of previous research (Tong, 2014) is improved. The effect of eccentricity and residual stress is not considered. These does not affect collapse strength of

thick-walled pipe. It was studied by Bastola (2014). The key parameters which are expressed an exponential form are reflected in the prediction equation. The prediction equation consists of linear combination of each term. The first term in the prediction equation means that original plastic buckling equation and the second term means that the effect of ovality which is representative of initial imperfection. The final term means that the effect of hardening parameter. The strength is enhanced by second and final term. These terms is related to the post-buckling behavior. In this research, the strength enhancement was assumed that increment for the original plastic buckling pressure. Also, the effect of ovality and hardening parameter were multiplied by the original plastic buckling pressure in these terms. Because it was regarded as relative concept for the original term.

4.2.2 **Calibration using Parametric Study**

In this research, the prediction equation was obtained through the regression analysis. It was performed by IBM SPSS Statistics 23. It is one of the commonly used commercial program for regression analysis. It can be performed nonlinear regression analysis and get exact results. In this program, the Levenberg-Marquardt method is used for nonlinear regression analysis. Levenberg (1944) and later Marquardt (1963) proposed to this method using a *damped Gauss-Newton method*.

The IBM SPSS Statistics 23 is used to fit Equation (29) to results of parametric study. The constants in Equation (29) are tabulated in Table 7.

The maximum error when comparison between results of parametric study and collapse strength using Equation (29) is always less than 6.2% for all considered models. Also, the R-square is 0.994. It means that suitability of the prediction equation. The equation of R-square is defined as Equation (31). Thus, this model has enough accuracy to predict collapse strength of thick-walled pipe.

Table 7 Values of the Constants to be used in Prediction Equation

Constants	a	b	c	d	e	f
Values	0.39	0.902	1.311	-0.026	1.445	-0.353
Constants	g	h	i	j	k	
Values	0.73	32.841	0.383	6.628	1.44	

$$R^2 = 1 - \frac{Error \sum of\ Squares}{Total \sum of\ Squares} = 1 - \frac{\Sigma\left(y_i - \hat{y}_i\right)^2}{\Sigma\left(y_i - \overline{y}\right)^2} \tag{31}$$

4.3 Application of Prediction Equation

In this section, the collapse strength of thick-walled pipe is evaluated using prediction equation calibrated in Section 4.2. The accuracy of this prediction equation was verified in Section 4.2. One of the key parameters was changed and the others were fixed when the collapse strength was evaluated. In all Figures, the x-axis is the D/t ratios and the y-axis is the collapse strength.

First, the effects of ovality are shown in Figure 37 and Figure 38, respectively. Representatively, the comparison was performed in case of ovality which is 0.005, 0.01 and 0.02. The yield stress and hardening parameter are maintained constant. The line which is located in upper position means that collapse strength of steel pipe with small ovality. In case of steel pipe with D/t ratios between 10 and 15, the difference of collapse strength is constants regardless of D/t ratios. This tendency is similar in all analysis case. Second, the effects of yield stress are shown in Figure 39 and Figure 40, respectively. Yield stress of the steel grade such as API X65, X70 and X80 is tabulated in Table 6. The line which is located in lower position means that collapse strength of steel pipe with small yield stress. In case of steel pipe with D/t ratios between 10 and 15, the difference of collapse strength is big by yield stress when D/t ratios is smaller. The meaning of smaller D/t ratios is same with thicker steel pipe. Also, the quantity of collapse strength reduction is more bigger than that by ovality. This tendency is similar in all analysis case. However, the effect of yield stress is small at steel pipe with D/t ratios above 15. It is known through previous research. Accordingly, when the design of thick-walled pipe with D/t ratios below 15 is performed, the selection of appropriate yield stress will be a critical issue. Finally, the effects of hardening parameter are shown in Figure 41 and Figure 42, respectively. The line which is located in upper position means that collapse strength of steel pipe with small hardening parameter. In case of steel pipe with D/t ratios between 10 and 15, the difference of collapse strength is extremely big by hardening parameter when D/t ratios is smaller. Especially, the difference of collapse strength is big with hardening parameter

between 8 and 14. This tendency is similar in all analysis case. However, there is no effects of hardening parameter with D/t ratios above 15. It is evident that elastic buckling irrelevant to the post-buckling behavior. Therefore, using current design standard, the exact collapse strength can be predicted when D/t ratios exceeds 15. However, the hardening parameter should be considered for exact evaluation of thick-walled pipe with D/t ratios below 15.

As results, when designing to thick-walled pipe, yield stress and hardening parameter are more important than initial imperfection such as ovality.

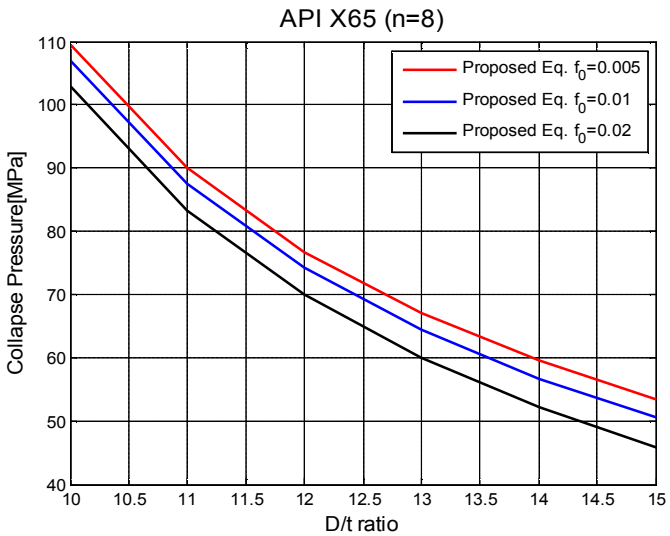

Figure 37 Effect of Ovality on Collapse Strength (σ_y = 448MPa, n=8)

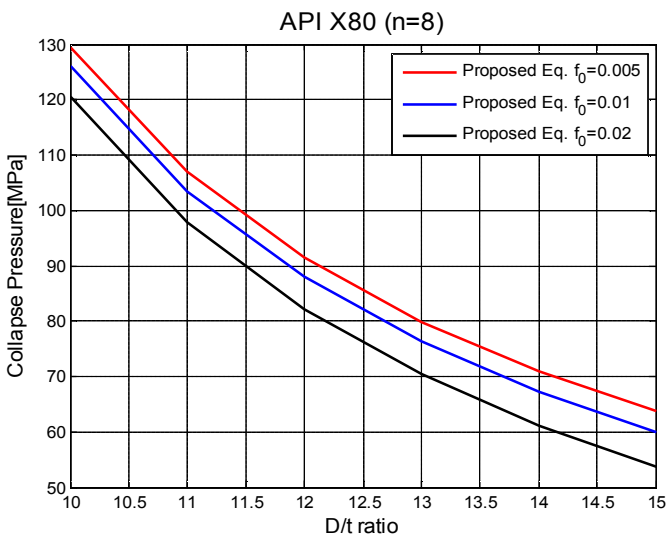

Figure 38 Effect of Ovality on Collapse Strength (σ_y = 552MPa, n=8)

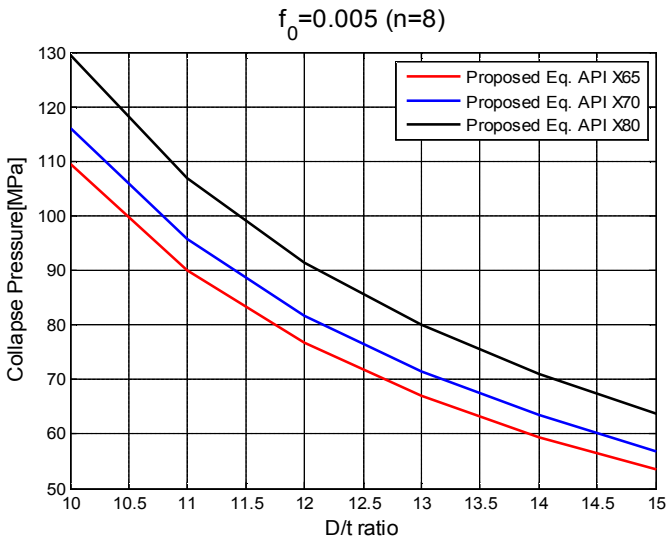

Figure 39 Effect of Yield stress on Collapse Strength (f_0 = 0.005, n=8)

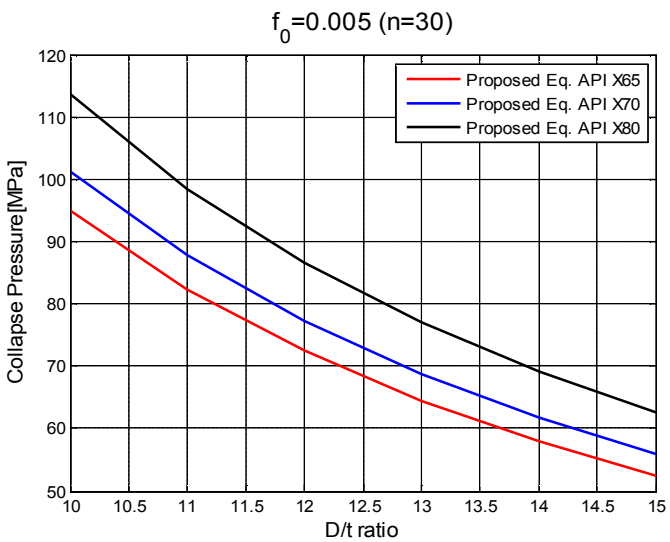

Figure 40 Effect of Yield Stress on Collapse Strength (f_0 = 0.005, n=30)

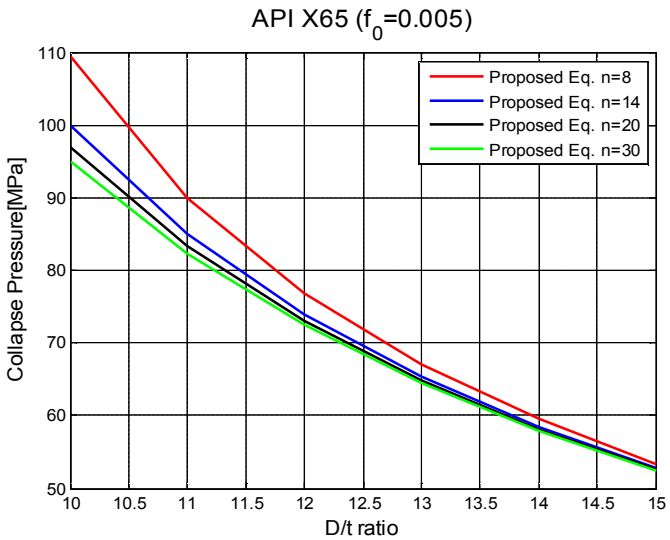

Figure 41 Effect of Hardening Parameter on Collapse Strength

(σ_y = 448MPa, f_0=0.005)

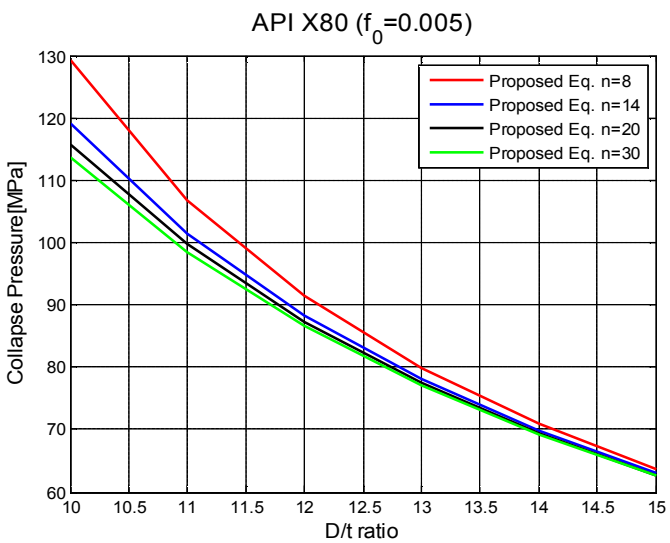

Figure 42 Effect of Hardening Parameter on Collapse Strength

(σ_y = 552MPa, f_0=0.005)

5 Conclusions

In this research, a comparison between failure modes of thick-walled and thin-walled pipes was performed. The collapse is one of the limit state of offshore steel pipe in the construction phase. The current design standard to provide collapse equation is based on linear elastic properties. These properties are relevant to failure mode of thin-walled pipe and are assumed as follows: (1) all the stresses on the pipe are concentrated into four regions where the plastic hinges is occurred (2) the collapse occurs when the stresses concentrated into four regions reach the yield stress. However, the failure mode of thick-walled pipe is relevant to nonlinear inelastic properties. Therefore, the current design standard has limitations to accurate evaluate the collapse strength. The collapse strength of a thick-walled pipe is determined by post-buckling behavior which causes increased strength after buckling occurs. This increased strength is determined by the material and geometric nonlinear properties. In this research, the failure mode of the thick-walled pipe was assumed as follows:

- The buckling stress is bigger than the yield stress when plastic hardening effect is considered.

- The collapse strength of thick-walled pipes differs from hardening parameter.

- The external pressure is distributed across the whole cross-section because of geometric properties.

FEA was performed considering material and geometric nonlinear properties to verify the assumptions. The collapse strength was defined as maximum load in the load-displacement curve. At thin-walled pipe with D/t ratio = 30, the failure mode was similar to that of current design standard. However, at thick-walled pipe with D/t ratio = 10, the failure mode was represented assumptions which are relevant to nonlinear inelastic properties. The external pressure was distributed around the whole cross-section, and the collapse was occurred within the plastic range of the material model.

The prediction equation, which was used for evaluation of the collapse strength of thick-walled pipe with D/t ratios below 15, was proposed. The key parameters were defined as D/t ratio, ovality, yield stress and hardening parameter. The range of parameters was determined by actual specifications used in the offshore industry. In order to perform regression analysis, a total of 360 cases were analyzed and an accurate prediction equation used for the design of a thick-walled pipe was derived.

The collapse strength of thick-walled pipe was analyzed using the prediction equation. The material properties such as yield stress and hardening parameter were more important than initial imperfections. However, in case that D/t ratio is bigger than 15, the collapse strength is not influenced by the hardening parameters. This research suggests that material model should be exactly considered when designing a thick-walled pipe with D/t ratios below 15.

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초 록

이 논문에서는 두꺼운 강관과 얇은 강관의 파괴 모드를 좌굴 이론에 기반하여 비교하고, 유한요소해석을 통해 확인하였다. 또한, 두꺼운 강관의 설계에 사용할 수 있는 극한강도 평가식을 제안하였다. 특히 해저 강관은 내부가 비어있는 상태로 시공되기 때문에 외부 정수압에 취약하다. 따라서 국부좌굴에 의한 해저강관의 붕괴는 주요 한계 상태가 된다. 이러한 붕괴 현상은 강관의 재료적·기하적 특성에 의해 결정된다. 또한 이러한 특성은 선형 및 비선형 특성으로 구분할 수 있다. 얇은 강관의 파괴모드는 선형 탄성 특성에 의해 결정되기 때문에 해석적 방법을 통해 극한강도를 평가할 수 있다. 하지만 두꺼운 강관의 파괴모드는 비선형 비탄성 특성에 의해 결정된다. 이러한 특성들로 인해 두꺼운 강관의 정확한 극한강도를 해석적인 방법으로 평가하는 데 한계가 있다. 두꺼운 강관의 극한강도를 정확하게 예측하기 위해, 재료적·기하적 비선형 특성을 고려하여 총 360가지 경우의 3차원 유한요소해석을 수행하였다. 그 결과, 두꺼운 강관의 파괴모드는 재료적·기하적 비선형 특성과 밀접한 관련이 있는 후좌굴 거동에 의해 지배되는 것을 확인하였다. 이러한 후좌굴 거동은 강관의 강도 증가 효과를 유발한다. 제안된 극한강도 평가식을 이용하여 두꺼운 강관의 극한강도를 평가한 결과 두께에 대한 직경 비율 (D/t ratios) 이 15 이하인 경우, 진원도와 같은 초기결함의 영향보다 항복응력과 경화지수 같은 재료 모델의 영향이 큰 것으로 나타났다. 따라서 두꺼운 강관을 설계할 때, 소성구간이 포함된 정확한 재료모델을 사용하는 것이 중요하다.

주요어 : 두꺼운 강관, 붕괴, 국부좌굴, 극한강도, 후좌굴 거동, 극한강도 평가식

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