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Elastic-plastic Buckling Analysis of Q690 High Strength Steel Tubes Under Global Bending

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Abstract: In recent years, high-strength steel has been used extensively for infrastructures because of its many advantages, such as its ductility and strain-hardening properties, which are inferior to those of ordinary structural steel, and the small dimensions of the structural elements, which lead to greater freedom and elegance in design, resulting in lighter structures. In practice, imperfections such as residual stresses due to the welding process and pre-buckling mode imperfections are inevitable in cylindrical structures made of high-strength steel. A small imperfection amplitude can lead to a disproportionate reduction in buckling strength. Therefore, imperfection sensitivity should be considered when studying the buckling behaviour of the shell. The influence of the combined residual stress and pre-buckling mode imperfection on the buckling behaviour of Q690 high strength steel cylindrical shell under global bending has not yet been investigated and described for all dimensions. In this paper, the combined imperfections influences on the buckling behaviour of high-strength steel cylindrical shell in global bending in the elastic-plastic range are investigated. Using the ABAQUS fine elements software, perfect cylinders with a constant length to thickness ratio equal to 7 and a radius to thickness ratio in the range $10 \leq r/t \leq 700$ were considered to perform the linear bifurcation analysis (LBA) and the geometric nonlinear analysis (GNA). The non-linear analysis with imperfections (GNIA) and the geometric and material non-linear analysis with imperfections (GMNIA) were then performed considering imperfection amplitudes between 0.01 and 2 to derive the critical buckling loads known as bifurcation point for the models with different aspect ratio. The influences of the combined imperfections show that moderately and very thin cylinders are very sensitive to the increase of the pre-buckling mode imperfection amplitude and their buckling strength is insensitive to plasticity. For thick cylinders, the effect of plasticity is more consistent, while the buckling strength is not significantly affected by the increase in pre-buckling mode imperfection amplitude. The main objective is to predict the buckling sensitivity of cylinders under the influence of combined residual stress and pre-buckling mode imperfection. The obtained results, comments and conclusions intend to allow for safer.

Keywords: High Strength Steel Cylinders, Global Bending, Pre-buckling Mode Imperfection, Residual Stress, Imperfections Sensitivity

1. Introduction

Due to their lower ductility and strain- hardening properties compared to normal structural steel, their small size of structural elements leading to more freedom and elegance in design and thus lighter structures, high strength steel (HSS) has recently been used in a variety of infrastructures compared to normal steel. In recent years, buckling and stability analysis of cylindrical shells has been a hot research topic where local or global buckling of the shell was considered as the cause of failure. Many research papers dealing with the imperfection sensitivity of cylinders under axial compression [1-9] and a few on cylindrical shells under global bending [10-13] have been quite well documented by numerous analytical and experimental studies. Shell structures under global bending develop a compression on top while the bottom is in tension (Figure 1). They show a distinctly non-linear behaviour due to the coupling between the ovalisation of the cross-section and the local bifurcation buckling [1, 14]. Under different loading situations, these shells can buckle in different ways. For axial compressive stresses, the buckling takes a small form in a small area that gradually propagates to the critical value of the compressive stress, which extends over a large zone to form axial buckling in compression. For thicker shells, in the case of a perfect cylinder in the elastic-plastic range, the strength limit or first yielding occurs for the moment having the value given in Eq.1.

$$M_Y = \pi r^2 t \sigma_y \tag{1}$$

With σ_y the yield stress, t the thickness and r the radius of the structure. The full plasticity M_P is obtained when the following equations are satisfied.

$$M_P = 4r^2 t \sigma_y \tag{2}$$

For thicker tubes:

$$M_P = \frac{4}{3}\sigma_Y \left[\left(r + \frac{t}{2} \right)^3 - \left(r - \frac{t}{2} \right)^3 \right] \tag{3}$$

One of the most challenging aspects of shell design is the imperfection-sensitivity analysis.

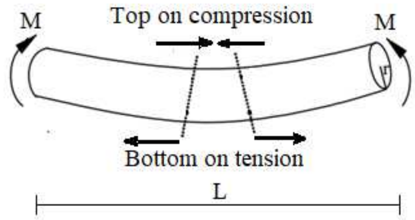


Figure 1. *Deformation of cylinder in bending.*

Recently, finite element technology has enabled the study of the temperature field during welding in conjunction with numerical simulations of weld residual stresses and deformation due to welding [15-19]. In addition, the study of residual stresses in high strength steel with a nominal yield strength of 690 MPa or 700 MPa has focused on box-shaped, H-shaped cross-sections [20-23] and on cylindrical shell structures where they have been mathematically designed by experiment [24] and simulation [25]. Welded circular high-strength steel (HSS) tubes are increasingly used in truss, grid, net shell, power transmission and tower structures with the advancement of high strength steel technology [26]. The residual stress repartition along the cross section and its amplitude are influenced by several factors, including the shape and size of the cross-section, the welding method and the material properties. Ballio et al [27] found that residual stresses affect the compressive stability, the fatigue failure, the brittle fracture and the stress corrosion cracking. Yang et al [25] investigated the residual stress distribution in welded circular hollow sections with a yield strength of 690 MPa using two different experimental approaches for galvanized and non-galvanized tubes. They modelled the residual stress with Equations 4 and 5.

For galvanize tube

$$\sigma_r / \sigma_y = \begin{cases} -6.92x + 0.7; \text{.........}(0 \le x \le 0.12) \\ 0.22x - 0.16; \text{..........}(0.12 \le x \le 1) \end{cases} \tag{4}$$

For non-galvanize tube

$$\sigma_r / \sigma_y = \begin{cases} -10x + 1; \text{.................}(0 \le x \le 0.12) \\ 0.32x - 0.24; \text{............}(0.12 \le x \le 1) \end{cases} \tag{5}$$

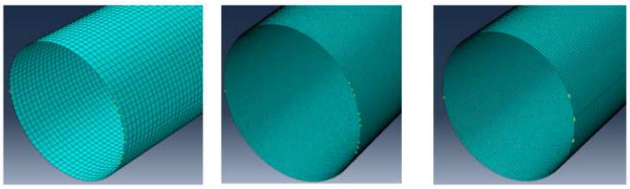
Wei Yanlei et al. have shown that residual stress does not significantly affect the strength (-1.38% to -0.55%) of some cylindrical shell structures [28].

Geometric nonlinearity can cause the strength of a perfectly elastic shell to decrease under global bending. Moreover, as the mode-warped shape evolves, it is difficult to characterize it in a specific and reproducible way [2, 14, 29]. The incremental mode at the limiting load point (bifurcation point) or the NBM of nonlinear buckling can be significantly different from the linear bifurcation mode (LBM). Depending on the nonlinear analytical results of the perfect structure, the incremental mode corresponds to the bifurcation point (Figure 2) therefore, all incremental modes obtained before the bifurcation point can be used as pre-buckling mode imperfections and those after the bifurcation point as post-buckling mode imperfections. Some studies have used shells based on the post-buckling mode as imperfections [30-32]. In this study, the bifurcation-buckling mode or the pre-buckling mode imperfections with an imperfection amplitude in the range of $0.01 \le \delta_0 / t \le 2$ are considered because they are more practical and can significantly affect the strength of the cylinders. The ABAQUS fine elements software was used to perform the relevant calculations and extract the results for analysis. In this paper, the effect of the combined residual stress (applied as a predefined compressive stress) and the pre-buckling mode imperfection on the strength of the cylindrical HSS structure under global bending is investigated. Linear bifurcation analysis (LBA), Geometrically Nonlinear Analysis (GNA), Geometrically Nonlinear Analysis with imperfections (GNIA) and Geometrically and material nonlinear analysis with imperfections (GMNIA) were performed on short, medium and long cylinders to investigate the sensitivity of imperfections, which are useful for better understanding and prediction of the buckling behaviour of such structures.

2. Numerical Modelling Using Finite Elements

The commercial finite element analysis software ABAQUS [35] was used to model and analyze cylinders with different aspect ratios. The four-node reduced-integration (S4R) shell elements was used to design the cylindrical shell tubes. A reference point was created at the center of each base surface, which was connected to the edge surface of the cylinder via a rigid kinematic coupling. It was only allowed to rotate around the y1 axis of the (O, x1, y1, z) coordinate system, while the other degrees of freedom were restricted. (O, x1, y1, z) is a subsystem created by rotating the x and y-axis (rotation of $\Psi = 0.12\pi = 21.6^0$) about the z-axis to facilitate the application of loads (moment M) such that the compressive area of the pipe due to bending corresponds to the compressive area due to the maximum residual compressive stress caused by welding. It is assumed that the model is made of high strength steel Q690 with modulus of elasticity E of $2\text{x}10^5$N/mm^2, Poisson's ratio of 0.235, density of $7.85\text{x}10^{-6}$ kg/mm^{-3} and yield stress of 690 MPa. With a unit thickness (t=1mm), the ratio of length to radius was assumed to be constant (L/r =7). The ratio of radius to thickness (r/t) was considered in a range of $100 \le r/t \le 700$. A study of mesh convergence was carried out by considering that a chosen mesh size can be considered as an acceptable result if the change in critical buckling load is less than 1% of the further refinement of the mesh [33], therefore the mesh size has been determined as follows:

$$\lambda = 2.44\sqrt{rt} \tag{6}$$



(a) r/t=10 (b) r/t=100 (c) r/t=700

Figure 2. *Good fine mesh used for some cylinders.*

For each length-to-radius ratio, a linear bifurcation analysis (LBA) was performed on perfect cylinders by applying a limiting moment M_{y1} as a load to determine the eigenvalue of the first EigenMode ($\mathcal{E}$). The critical buckling moment M_{cr} (sometime expressed as M_{LBA}) was determined with equation 7.

$$M_{cr} = M_{LBA} = \varepsilon M_{Y1} \tag{7}$$

This critical buckling moment was then used as the load for performing Geometric Nonlinear Analysis (GNA), Geometric Nonlinear Analysis with Imperfections (GNIA) and Geometric and Material Nonlinear Analysis with Imperfections (GMNIA). The modified arc length method of Riks [34] was used. The first reported eigenvalue of the global stiffness matrix corresponding to the local bifurcation point or global limit called *LPF* (Load Proportional Factor), was extracted and used to calculate the nonlinear buckling moment (M_k) using Equation 8.

$$M_k = LPF \times M_{LBA} \tag{8}$$

GNA was performed for all models and the corresponding bifurcation point was identified. This step was of particular interest because the increment of the bifurcation point (Figure 3) is used as predefined pre- buckling imperfection in combination with the residual stress of the perfect cylinder for the GMNIA. The maximum deviation of the imperfect shell in the direction normal to the ideal geometry is defined as the imperfection amplitude δ_0/t. To define an imperfection with an amplitude of δ_0/t at a given position on the load-displacement curve, the largest radial displacement U_{max} has to be extracted and the imperfection amplitude δ_0/t to U_{max} ratio known as the fully deformed shape k is given as follows:

$$k = \delta_0/(t.U_{\max}) \tag{9}$$

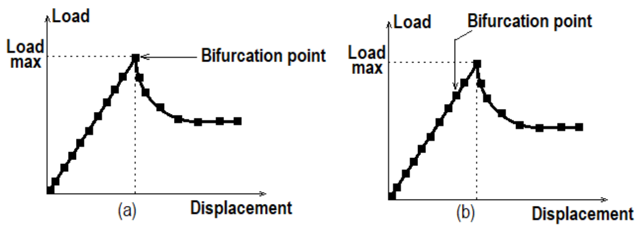


Figure 3. *Points on load-displacement path of perfect shell to define imperfection forms.*

The residual stress from the welding fabrication process was simplified and assumed to be equivalent to a pure compressive stress (σr); with a small effect of strength reduction r_d ($-5\% \le rd \le 0$). The residual stress was applied as a predefined longitudinal stress on small shell partitions during GNIA.

$$r_d = 100.(M_{GNIA} - M_{GNA})/M_{GNA} \tag{10}$$

Where M_{GNIA} is the moment at bifurcation for GNIA and M_{GNA} is the moment at bifurcation point for GNA.

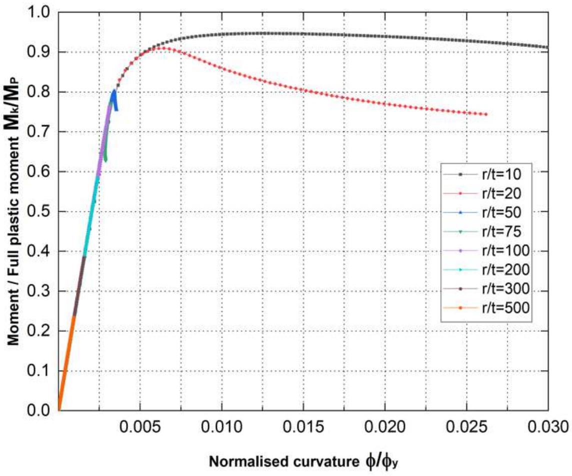
Table 1. *Equivalent compressive stress adopted and its influences.*

r/t	10	20	50	75	100	150	200	300	400	500	700
σ_r	14	14	13	13	10	10	9	7	6	7	3.5
M_{GNA}	0.228	0.53	1.70	2.84	3.75	5.64	7.56	11.2	15.1	18.8	26.4
M_{GNIA}	0.227	0.518	1.69	2.74	3.62	5.48	7.19	10.7	14.4	18.1	25.5
r_d	-0.3	-2.3	-1.1	-3.4	-3.3	-2.8	-4.9	-4.7	-4.3	-3.7	-3.4

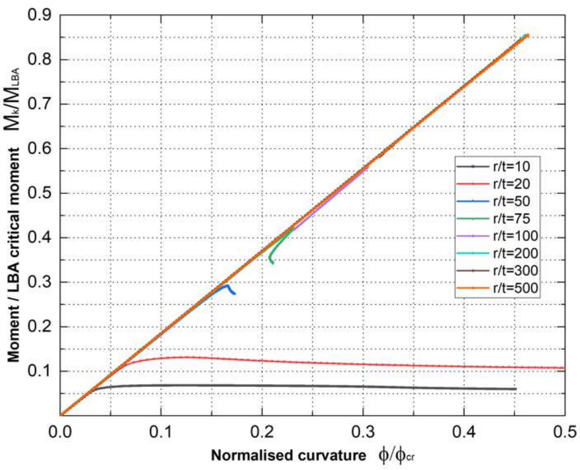
Plasticity (σ_y = 690MPa) was considered when performing GMNIA. The nonlinear or pre-buckling mode imperfection (Eq.9) with an amplitude δ_0/t in the range of $0.01 \le \delta_0/t \le 2$, combined with the compressive stress (equivalent to the residual stress from the welding process) was applied as the initial imperfection. The critical GMNIA buckling moments of all models with different imperfection amplitudes were extracted and used to derive the imperfection sensitivity curves.

3. Results and Discussion

3.1. Moment-Curvature Curves



(a)

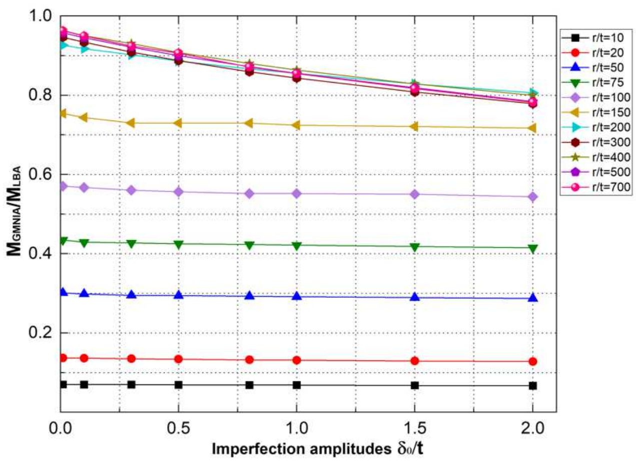


(b)

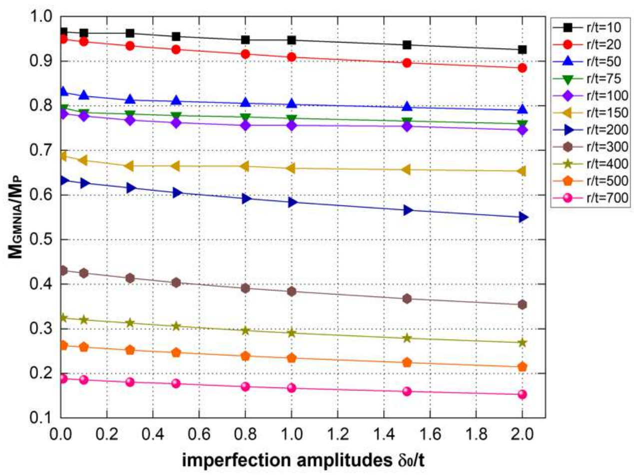
Figure 4. *Moment-curvature curves for different radius-to thickness ratios (δ_0/t =1).*

Figure 4 shows how the shape of the moment-curvature curve changes as the ratio of radius to thickness varies. In this case, the imperfection amplitude δ_0/t =1 of the pre-buckling mode imperfection was considered in combination with the residual stress. The relationship between moment and curvature transitions from a smooth, reasonably ductile response to bifurcation buckling with a steep drop after buckling as the radius to thickness ratio transitions from a thick cylinder (r/t=10) to a moderately thin cylinder (r/t=100) and then to a very thin cylinder (r/t =700, not plotted). In Figure 4(a), the full plastic moment (Eq.3) was used to normalize the bending moments M_{GMNIA} of GMNIA of the shell. Since the imperfection amplitude of δ_0/t =1 is such a geometric deviation for r/t=10, it does not reach the full plastic moment of the perfect geometry. Because of the complicated pattern of bending and stretching that yields at the deep imperfection, it remains ductile at a plateau near M_k/M_P =0.95. At slightly thinner cylinders (r/t=20), ductility begins to fade and strength is limited by a bifurcation with a softer response after buckling (r/t=50). The bifurcation features a significant post-buckling fall by *r/t* =75; it is repeated as the shell grows thinner. In Figure 4(b), where the curvature ϕ has been normalized to the curvature at the bifurcation from the linear theory ϕ_{cr} (ϕ_{cr} $=M_{cr}/EI$), the bending moment has been normalized with respect to the linear bifurcation moment from Eq.7. The data in Figure 4(a) were plotted differently in Figure 4(b) to show the behaviour of the thinner shells. Under plastic conditions, the thicker shells bifurcate, and this elastic-plastic buckling occurs over the entire range 50 ≤ r/t < 200 for δ_0/t =1. Cylinders with r/t ≥ 100 all reach similar moments at the bifurcation, occurring elastically near M_k/M_{LBA}=0.85.

The same procedure is used for the next parts. The bending moment (M_{GMNIA}) of the bifurcation point is taken into account. The whole range of the pre-buckling mode imperfection amplitude (0.01≤ δ_0/t ≤2) in combination with the compressive residual stress and all radius to thickness ratios (10 ≤ r/t ≤ 700) are considered to investigate and understand well the behaviour of the cylinders.



(a)



(b)

Figure 5. *Pre-buckling imperfection sensitivity curves for different r/t of cylinders with predefined compressive stress under global bending.*

3.2. Imperfection Sensitivity Curves for Cylinders with Different Aspect Ratios

Figure 5 shows the imperfection sensitivity curves for different radius to thickness ratios of cylinders with predefined compressive stress (corresponding to the residual stress from the welding process) and different pre-buckling mode imperfection amplitudes. The increase in imperfection amplitude leads to a greater loss of strength, which is more effective for moderately and very thin cylinders. In Figure 5(a), where the moment M_{GMNIA} has been normalized by the critical linear moment M_{LBA}, the effects of imperfection appear to be very similar for cylinders in the range $200 \leq r/t \leq 700$. It is difficult to distinguish the different paths of cylinders in this similar range, so the same data have been plotted in Figure 5(b), with M_{GMNIA} normalized by the full plastic moment Mp. The curves for the thick cylinders show the effect of plasticity and imperfection amplitude on buckling strength, while the curves for the medium and thin cylinders show only the effect of imperfection amplitude due to elastic buckling, which occurs in these cylinders even when plasticity is taken into account.

4. Conclusion

In this paper, high-strength steel with Q690 (having a constant yield strength of 690MPa) under global bending was studied. The pre-buckling deformation mode of the perfect structure combined with predefined compressive stress (equivalent to the longitudinal residual stress from the welding fabrication process) was applied as predefined imperfections during the GMNIA. The influences of the combined imperfections show that the loss of strength due to the increase of the pre-buckling mode imperfection amplitude is more effective for moderately and very thin cylinders where the buckling strength is not affected by plasticity. For thick cylinders, the effect of plasticity is more consequent while the combined imperfections do not affect the buckling strength considerably with the increase of the pre-buckling mode imperfection amplitude. This paper describes the behavior in the elastic-plastic range of high-strength steel cylinders under global bending subject to combined pre-buckling mode imperfections and residual stress. It demonstrates how the imperfections influences can be used to understand, predict, and accurately describe the complex mechanical behaviour of cylindrical shells under certain loading conditions.

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