Buckling of Stiffened Thin Walled Cylindrical Tanks with Shell Imperfections due to Global Shear and Seismic Loads

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15 WCEE
LISBOA 2012

SUMMARY
Thin walled cylindrical shells are important components of industrial structures such as liquid storage tanks, silos, etc. Shell buckling is usually a major failure mode of thin walled shells under extreme loads such as earthquakes. Longitudinal and radial stiffeners are generally used in order to increase buckling capacity of thin walled shells. During an earthquake, cylindrical shells may experience global shear and suffer shear buckling. Buckling of thin walled shells is highly dependent to imperfections. In this study buckling of imperfect cylindrical stiffened tanks due to global shear and seismic loads are studied. To this end nonlinear FE static analyses have been performed in order to estimate buckling capacity of imperfect cylindrical stiffened tanks due to global shear. Herein cylindrical tanks of a constant height and different height to diameter (H/D) ratios were considered. Different arrangements of stiffeners were considered for each tank. Random patterns of imperfection with moderate imperfection amplitude were considered in all tanks. Design relations have been presented based on the results of numerical analyses. Finally, time history analyses were performed in order to evaluate the validity of suggested design relations for buckling of cylindrical stiffened tanks due to seismic loads.

Keywords: Stiffened cylindrical tank, Buckling, Numerical Analysis

1. INTRODUCTION

Cylindrical shells are important components of industrial plants such as oil refineries and petrochemical plants. Performance of shell structures during the past earthquakes revealed that these structures are seismically vulnerable. The most common failure mode of thin steel shells is buckling. Since 1900s several analytical and experimental investigations have conducted in order to estimate the buckling strength of cylindrical shells. The buckling strength of cylindrical shells was independently founded by Lorenz (1908), Timoshenko (1910) and Southwell (1914) for perfect elastic cylindrical shells under axial compression. The buckling strength predicted by above mentioned researches is known as classical buckling strength. The above mentioned investigations were followed by several studies for imperfect shells (Koiter (1963), Yamaki (1984) and Rotter (1997)). Results of these studies showed that buckling capacity of imperfect shells are much less than those estimated by classical relations. For the safe and reliable design of shell structures (e.g. cylindrical storage tanks) for withstanding earthquakes, it is important to understand and the stability of vertical axis cylindrical shells under both static and dynamic transverse loading. A horizontal load applied to a vertical cylindrical shell is termed as transverse shear or global shear. Since pre buckling deformations due to global shear are not axisymmetric, shear buckling is more complex than buckling due to the axial loads (Mitchel et al., 2004).

In order to calculate the elastic critical shear stress the following relations can be used (ENV-1993-1-6, 1999):

$$\tau_e = 0.75\sqrt{\frac{1}{\omega}}\frac{Et}{r} \tag{1-1}$$

In which E, t and r are Modulus of elasticity, shell thickness and radius respectively. The parameter ω can be calculated as follows:

$$\omega = \frac{L}{\sqrt{rt}} \quad (1\text{-}2)$$

Hence the classic global shear load (Q_{cl}) can be calculated as follows:

$$Q_{cl} = \pi r t \tau_e \quad (1\text{-}3)$$

Stiffeners are useful elements to improve buckling behavior of cylindrical shells. Stringer stiffeners are served to increase buckling capacity and ring stiffeners useful to improve the local buckling strength of cylinders. Stiffened shells are used in both aerospace and structural engineering. Useful information about performance of stiffened cylinders can be followed in Green and Nelson (1982) and Kendrik (1985) and Galambos (1998).

2. NUMERICAL ANALYSIS

Nonlinear static and time history analyses were conducted in order to investigate the buckling of stiffened cylindrical shells. Herein ANSYS multipurpose FEM software was used. Four-node SHELL 181 elements were used in order to model cylindrical shells. These elements are capable of considering large displacements. Cylindrical shells of constant height (H=10m) and different diameters (D=20, 22, 23, 24, 25m) were considered. In all of the models the thickness of shell was assumed to be 20mm. The vertical stiffeners 10m in height, 20mm in thickness and 100mm in width. A bilinear material model with kinematic hardening was considered. The yield stress of steel shell was considered to be 240 Mpa and the tangent modulus was assumed to be 2% of linear elastic modulus of material.

2.1. Static analyses

Nonlinear static analysis carried out in order to estimate global shear buckling strength and post buckling behavior of stiffened shells. To this end incremental transverse displacements applied to the top of vertical cylindrical shells.

2.2. Time history analyses

Time history analyses were carried out in order to estimate the buckling capacity of stiffened shells. Herein acceleration time history of S-E component of Tabas seismic events was normalized to 0.2g, 0.4g, 0.6g and 0.8g and used for dynamic analyses. The added mass method was used in order to consider the effect of the mass of contained liquid. Herein the contained liquid was assumed to be water.

3. RESULTS

In order to investigate the effect of vertical stiffeners on global shear buckling force of cylindrical shells load-displacement relationships of stiffened shells were compared to un-stiffened ones. Results of this investigation revealed that unlike axially compressed cylinders, stiffeners may decrease the buckling strength of cylinders due to global shear. Figure 1 indicates the comparison of load pre- and post buckling behavior of an stiffened and an un-stiffened shells of same geometric specification (D=20m, t=20mm and H=10m). It is worth mentioning that the distance between vertical stiffeners in the stiffened shell is 2m. As indicated in Figure 1, the initial stiffness of stiffened shell is greater than un-stiffened one. Meanwhile the bifurcation load of the stiffened shell is about 0.9 of buckling load of un-stiffened shell. In other words although the stiffened shells is stiffer than the un-stiffened one, its buckling capacity due to the shear load is slightly less than un-stiffened shell. Furthermore the post buckling path of the un-stiffened shell is more stable than that of stiffened shell. Such behavior is completely different with behavior of stiffened shells due to axial compression. The main reason for such a behavior is susceptibility of stiffeners to buckling and noticeable stress concentration in shell-to-stiffener junction. In most of the cases the cylindrical shells buckled in stiffened areas and in some of them buckling of stiffener(s) happened prior to shell buckling (See Figure 2).

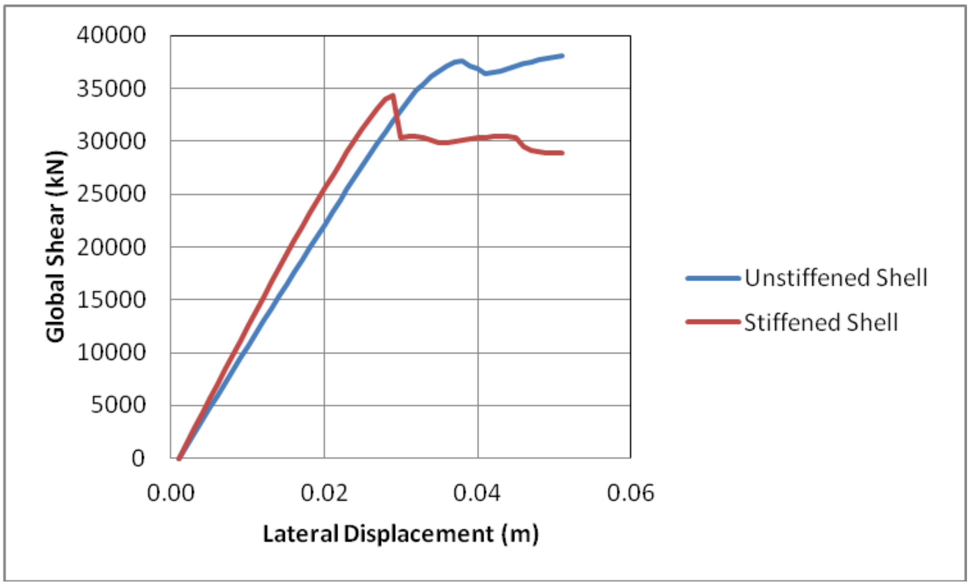

Figure 1. Load displacement relationship of a stiffened and an un-stiffened shell

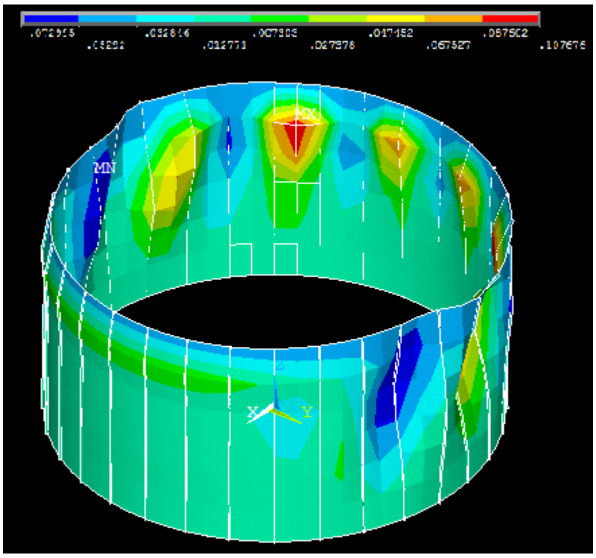

Figure 2. Post- buckling deformed shape of a stiffened cylindrical shell

In order to investigate the effect of distance of stiffeners on shear buckling behavior of stiffened shells different cylinders of the same geometrical specifications (D=20m, t=20mm) and different numbers of stiffeners were considered. Figure 3 shows the variation of shear buckling load of the stiffened shells versus distance of stiffeners. As indicated in this figure by decreasing the distance of vertical stiffeners the shear buckling capacity of the shell decreases especially for shells with stiffener distance less than 2.5m. It is also shown that by increasing the stiffener distance from 5m the buckling capacity of stiffened shells tend to that of un-stiffened shell.

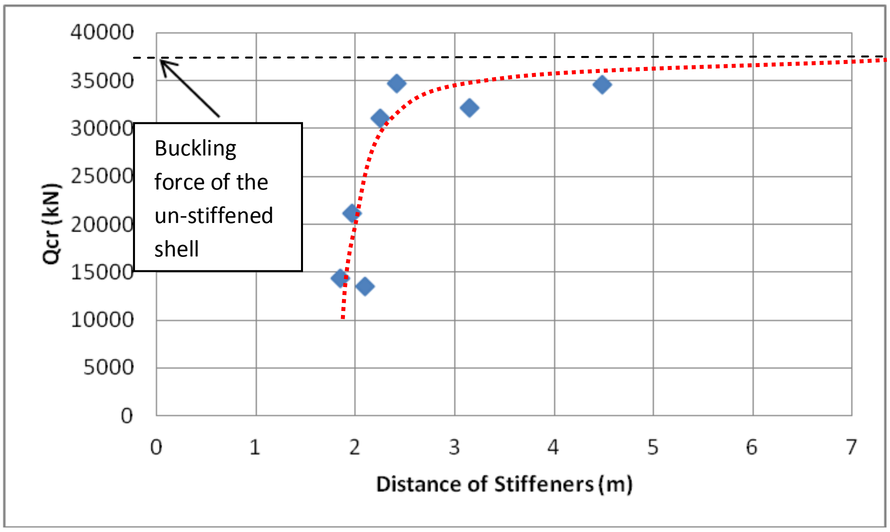

Figure 3. The effect of distance of vertical stiffeners on shear buckling capacity

In order to investigate the effect of geometrical specifications on buckling capacity of stiffened cylindrical shells due to global shear, the buckling capacity of stiffened cylindrical shells of various height to diameters (H/D), diameter to thicknesses (D/t) and the same number of stiffeners (N=32) were numerically computed. Figure 4 and 5 shows the variation of global shear buckling capacity of stiffened cylinders versus H/D and D/t respectively. As indicated in these figures there aren't meaningful relationship between buckling load and geometrical specification. This may happens because of susceptibility of shell buckling capacity to distance of stiffeners as discussed above.

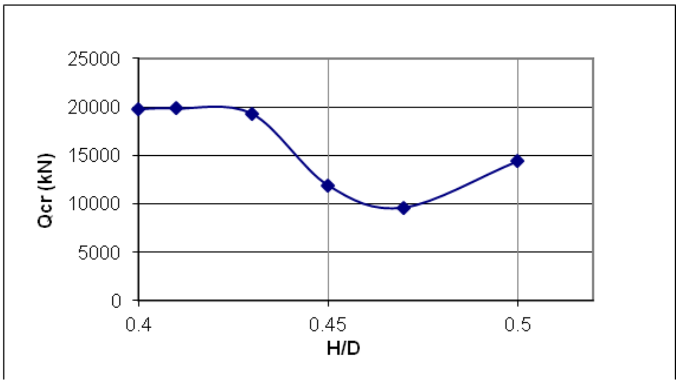

Figure 4. Variation of shear buckling capacity with H/D

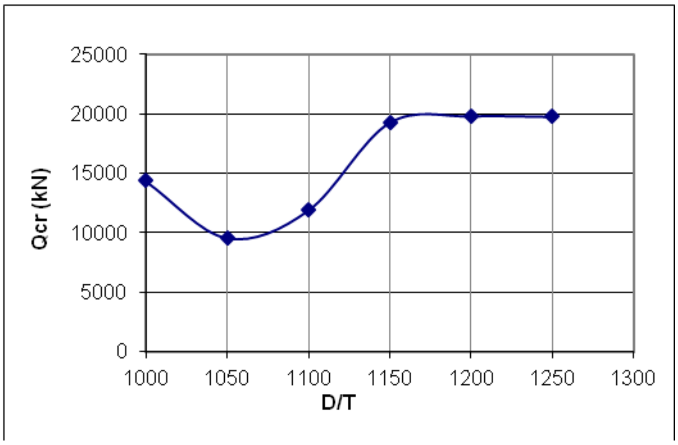

Figure 5. Variation of shear buckling capacity with D/T

In addition to the abovementioned static analyses, results of nonlinear dynamic analysis of cylindrical shells showed noticeable stress concentrations in stiffened shells. Figure 6 indicates the ratio of maximum compression stress of stiffened shell to that of un-stiffened cylinder due to different excitations.

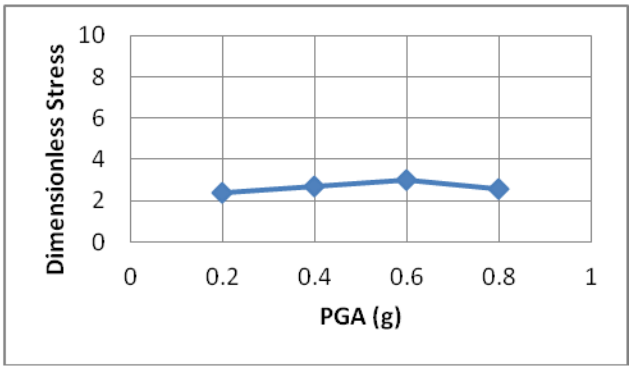

Figure 6. The effect of vertical stiffening on stress level of cylinders

In order to obtain design relation for buckling capacity of stiffened cylindrical shells, the classical shear buckling relation were considered and a modification factor was calculated to estimate buckling capacity of stiffened cylinders. To this end shear buckling capacity of stiffened shells were normalized to those estimated by Eq. (1-1). Figure 7 presents the values of normalized shear buckling capacities for different cylindrical shells. As indicated in these figures the normalized buckling capacities of un-stiffened shells are about 0.8 while for stiffened shells it varies between 0.2 and 0.57. In order to calculate the modification factor, an average minus standard deviation of normalized capacities can be used. As shown in figure 8 herein the modification factor of 2.46 can be considered for stiffened shells. In other words, based on the results of this study the following relation can be considered for design of stiffened shells against shear buckling:

$$Q_{cr} = 5.79Et^2\sqrt{\frac{1}{\omega}} \tag{3-1}$$

It is worth mentioning that above relation can be used for approximate estimation of shear buckling of cylindrical shells with vertical stiffeners. Furthermore this relation is valid for tanks with medium height. In order to obtain exact relation much more analyses are required.

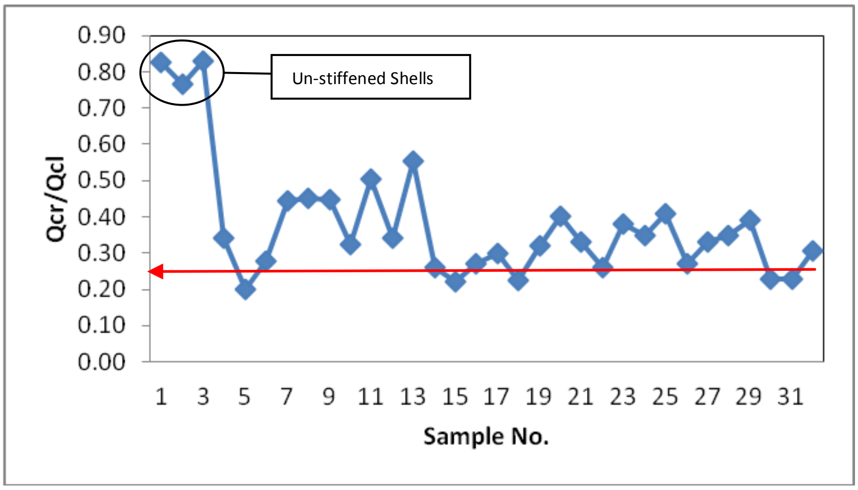

Figure 7. Normalized critical shear load in different cylindrical shells

4. CONCLUSIONS

Nonlinear static and time history analyses carried out in order to investigate buckling behavior of vertically stiffened shells due to global shear loading. Results of this study revealed that shear buckling capacity of vertically stiffened shells is considerably less than that of un-stiffened shells. Based combined numerical analysis and statistical methods a modification factor of 0.246 estimated for classical shear buckling of un-stiffened shells for considering the effect of vertical stiffeners. The design relation presented herein can be used an approximate formula. To obtain more exact relations more analyses and experiments are required.

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