Numerical Study on the Serviceability Performance of Unstiffened and Stiffened Steel Plates

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Abstract: In this paper, the effects of transverse stiffeners for improving the buckling and post-buckling behaviors of thin steel plates under compressive loading have been investigated through consideration of two parameters, i.e. stiffeners number and height. Moreover, the deformations associated with the buckling stability of unstiffened and stiffened plates have been evaluated through detailed comparison. Numerous numerical models have been developed using ABAQUS and the buckling behavior has been studied through performing nonlinear static analyses. Plate’s largest deformation has been considered for comparison purposes which may not be necessarily located in the center of the plate surface. The use of stiffeners by and large increases the load-bearing capacity of the plates; however, it is shown that lack of proper detailing of stiffened plates may unfavorably result in the reduction of the load-bearing capacity and, in general, adversely affect the stability performance of such commonly-used slender members.

Key words: Plate, stiffener, buckling, post-buckling, numerical simulation.

1. Introduction

One of the major issues in design of thin plates reinforced by stiffeners is their stability against local buckling phenomenon which is caused due to excessive force at a point of plate. However, when the plates are used for spans with large lengths, this phenomenon can result in failure of the plate under much lower pressure than the global buckling pressure. Buckling is one of the most complex phenomena in solid mechanics. This phenomenon is a major issue in structures that are very thin and are located in areas under large compressive forces or stresses.

Timoshenko [1] explored the buckling of uniformly compressed rectangular plates that are simply supported along two opposite sides perpendicular to the direction of compression and having various edges along the other two sides. The various boundary conditions considered include SSSS, CSCS, FSSS, FSCS, and CSES where S, C, F, and E are indicative of simply supported, clamped (or built-in), free, and elastically restrained edges, respectively. The theoretical results were in good agreement with experimental results obtained by Bridget et al. [2]. Lundquist and Stowell [3] used the integration method to solve ESES plates by assuming that the surface deflection was the sum of a circular arc and a sine curve. They also discussed the critical load of ESFS plates by both integration method and the energy method by assuming that transverse deflection was the sum of a straight line and the cantilever deflection curve. Walker [4] used the Galerkin’s method to give accurate values of critical load for a number of edge conditions mentioned before. He also studied the stability of plates with ESFS boundary conditions. Investigations on the buckling of plates with all sorts of shapes, boundary and loading conditions have been reported in standard texts (e.g. Timoshenko and Gere [5], Bulson [6], research reports (e.g. Batdorf and Houbolt [7]). A theoretical and experimental study on the inelastic buckling strength of stiffened plates was reported by

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Fukomoto et al. [8]. The same researchers went on to perform a wide ranging parametric study that resulted in design guidance for stiffened plates based on relevant plate and stiffener dimensions [9]. The specific role of the stiffener geometry, particularly stiffener torsional stiffness has been the focus of tests [10] as well as further nonlinear finite element analysis. Xiang et al. [11] considered the elastic buckling of a uniaxially loaded rectangular plate with an internal line hinge. Using the Levy’s method, they succeeded in presenting the exact solution for many different boundary conditions such as SSSS, FSFS, CSCS, FSSS and SSCS. Recently, Khayat et al. [12] used semi-analytical finite strip method in order to investigate the buckling behavior of laminated composite deep as well as thick shells of revolution under follower forces which remain normal to the shell. In addition to the studies reported on elastic buckling, plastic buckling of plates has also been investigated by several researchers. Further information in this regard can be obtained from the studies reported by Shrivastava [13], Betten and Shin [14], Soh et al. [15], Chakrabarty [16], Wang et al. [17], Wang et al. [18], Yu et al. [19], Fernandes et al. [20], and Fernández et al. [21]. Some researchers have conducted comprehensive research on the buckling of unstiffened and stiffened steel plates that have been studied by Manco et al. [22], Shi et al. [23], Ozdemir et al. [24] and Gulizzi et al. [25]. A search of the literature reveals that although much work has been done, the buckling of rectangular plates subjected to end and intermediate loads remains hitherto untouched.

In this study, an innovative approach is taken to evaluate the buckling stability performance of stiffened steel plates through numerical simulations. Finite element analysis of the plate models is based upon the following assumptions:

- After bending, the cross-section of the panel remains undeformed;
- Cross-section of the middle line remains elastic;
- The proportion of the primary to secondary deformations of a hinge is plastic;
- The height of the stiffeners mounted on plates and determined based on the orthotropic plate theory, is adjusted in such a manner so that the global and local buckling modes synchronize with each other.

2. Characteristics of Plate Models and Simulation Details

The main objective of this study was to further investigate the effects of stiffeners on the plate deformation and buckling stability through nonlinear static analysis. To this end, 1,000 × 1,000 × 1 mm square plates with two clamped and two free edges, as shown in Fig. 1, were considered. The elasticity modulus and Poisson’s ratio of the steel material were taken as 2 × 10⁶ MPa and 0.3, respectively. The plates were stiffened by 1, 3, and 5 longitudinal stiffeners with 1 mm thickness, 1,000 mm length, and varying height. The stiffeners were placed in parallel on the mid-line as well as quarter-lines, and along the two edges of the plate and were considered to be fully connected to the plates. The characteristics of the plate models as well as the stiffeners are summarized in Table 1. As shown in the table, the plate models are labeled so that the characteristics of each model can be identified from the label. For example, the label 75F3 indicates that the plate has 3 stiffeners with fixed edge condition which are 75 mm high.

As shown in Table 1, the two varying parameters of this study include the stiffener height and location/number. These two parameters can play an important role in stability performance, serviceability performance, and economic efficiency of such thin-walled structures. One unstiffened plate, i.e. model F0, and several stiffened plates with 25, 50, 75, and 100 mm stiffener heights were considered. Moreover, the stiffened plates were considered to be stiffened by: (1) only one stiffener located on the plate mid-line, (2) three stiffeners with one located on the plate mid-line and two along the plate edges (end-lines), and (3) five stiffeners with one on the mid-line, two on
Fig. 1  Stiffening, loading, and support conditions of plate models.

Table 1  Characteristics of plate models.

| Plate model | Plate dimensions length × width × thickness (mm) | Stiffener dimensions length × height × thickness (mm) | Location of stiffeners |
|-------------|-------------------------------------------------|-----------------------------------------------------|------------------------|
| F0          | 1000 × 1000 × 1                                 | -                                                   | -                      |
| 25F1        | 1000 × 1000 × 1                                 | 1000 × 25 × 1                                       | Mid-line               |
| 25F3        | 1000 × 1000 × 1                                 | 1000 × 25 × 1                                       | Mid- and end-lines     |
| 25F5        | 1000 × 1000 × 1                                 | 1000 × 25 × 1                                       | Mid-, quarter-, and end-lines |
| 50F1        | 1000 × 1000 × 1                                 | 1000 × 50 × 1                                       | Mid-line               |
| 50F3        | 1000 × 1000 × 1                                 | 1000 × 50 × 1                                       | Mid- and end-lines     |
| 50F5        | 1000 × 1000 × 1                                 | 1000 × 50 × 1                                       | Mid-, quarter-, and end-lines |
| 75F1        | 1000 × 1000 × 1                                 | 1000 × 75 × 1                                       | Mid-line               |
| 75F3        | 1000 × 1000 × 1                                 | 1000 × 75 × 1                                       | Mid- and end-lines     |
| 75F5        | 1000 × 1000 × 1                                 | 1000 × 75 × 1                                       | Mid-, quarter-, and end-lines |
| 100F1       | 1000 × 1000 × 1                                 | 1000 × 100 × 1                                      | Mid-line               |
| 100F3       | 1000 × 1000 × 1                                 | 1000 × 100 × 1                                      | Mid- and end-lines     |
| 100F5       | 1000 × 1000 × 1                                 | 1000 × 100 × 1                                      | Mid-, quarter-, and end-lines |

The finite element models of the plates were developed using the ABAQUS software. S4R element was chosen for modeling the plates. This 4-node element possesses reduced integration and finite strain kinematics, which allows 5 integration points to be placed across the shell thickness. Furthermore, it is not dominated by in-plane bending, has hourglass control and also a sufficiently-low computation load which allows it to be used effectively for large-deformation problems. Additionally, in the finite element analysis, a pressure of 400 kgf/m² was applied on the plate models.

3. Discussion on Serviceability Performance of Plates

3.1 Assessment Using Finite Element Analysis Results

Buckling and/or out-of-plane deformation of thin-walled plates or plated elements can adversely affect the structural behavior and seismic performance of structures. In addition, serviceability considerations may govern the design of thin-walled structures in some cases. Such issues can be addressed by either using thick or stocky unstiffened plates, or using slender plates strengthened by stiffeners, or a combination of both aforementioned alternatives. On the other hand, design of cost-effective structures is of great importance. Overall, design of high-performing and cost-effective thin-walled plates or plates structural elements requires a good understanding of various behavioral aspect of such frequently-used structures. On this basis, this section focuses on the deformation and serviceability performance of the unstiffened and stiffened plate models.

The out-of-plane deformation contour plots of the considered plate models are shown in Fig. 2. The
values of out-of-plane displacement at the center of the plates are also illustrated in Fig. 3. From Fig. 3, it is evident that the stiffened plates have significantly lower central displacements compared to the unstiffened plate. In addition, increasing of the stiffener height from 25 mm to 100 mm and also the number of stiffeners from 1 to 3 to 5 is found to decrease the plate central displacement by 66% and 21%, respectively, on average.

In addition to evaluation of the out-of-plane displacements at the center of the plate models, the maximum out-of-plane displacements of the plate models, illustrated in Fig. 4, are also assessed in order to gain a better understanding of the unstiffened and stiffened plates serviceability performance.

Fig. 4 shows a slightly different approach in terms of maximum displacement performance of the plate models. As seen, the 25F1, 50F1, 75F1, and 100F1 models undergo slightly larger maximum displacements compared to the unstiffened F0 model.
Fig. 2 Out-of-plane deformation contour plots of plate models.
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Fig. 3  Out-of-plane displacements at center of plate models.

Fig. 4  Maximum out-of-plane displacements of plate models.

Furthermore, increasing of the mid-line stiffener height from 25 mm to 100 mm results in increasing of the plate maximum displacement, which is albeit insignificant. However, inclusion of 3 and 5 stiffeners lowers the maximum displacement by approximately 9% and 24%, respectively, on average. In addition, increasing of the number of stiffeners from 1 to 3 and 3 to 5 results in approximately 36% and 70% decreasing of the maximum displacement, respectively, on average. Overall, findings of this case study demonstrate that increasing of the number of stiffeners seems to be more effective in limiting the plate maximum displacement compared to increasing of the stiffener height.

3.2 Assessment Using $\Psi$, $\zeta$, $\Delta$, and $\Gamma$ Parameters

For further evaluation of the stiffeners effect, four $\Psi$, $\zeta$, $\Delta$, and $\Gamma$ parameters are defined. $\Psi$ is the percentage of changes of the stiffened plate’s cross-section relative to the sample without stiffener, $\zeta$ is the percentage of changes of the stiffened plate’s displacement relative to the unstiffened sample, $\Delta$ is the percentage of changes of the area amplifiers, and $\Gamma$ shows the percentage of changes of displacement relative to the number of
stiffeners. The negative and positive signs in displacement values are indicative of respective positive and negative effects of employment of stiffeners.

\[
\psi = \frac{A_X - A_0}{A_0} \times 100 \quad (x = 2550.75'100', \ i = 13') \quad (1)
\]

\[
\zeta = \frac{\delta_X - \delta_0}{\delta_0} \times 100 \quad (x = 2550.75'100', \ i = 13') \quad (2)
\]

\[
\Delta = \frac{A_X - A_{X(i-1)}}{A_X(i-1)} \quad (x = 2550.75'100', \ i = 13') \quad (3)
\]

\[
\Gamma = \frac{A_X - A_{X(i-1)}}{A_X(i-1)} \quad (x = 2550.75'100', \ i = 13') \quad (4)
\]

In these equations, \( A_X \) = total area of the plate with stiffeners, \( A_0 \) = area of the plate without stiffener, \( \delta_X \) = total displacement of the plate with stiffeners, and \( \delta_0 \) = displacement of the plate without stiffener. The calculation results are summarized in Tables 2 and 3.

It is found that using a stiffener can cause an increase in the maximum plate displacement; further, using three and five stiffeners has caused a decrease in the plate displacement for clamped boundary conditions. It is also found that for a plate with one stiffener, increasing of the stiffener height results in larger maximum displacement. In other words, a stiffener with 100 mm height experiences larger displacement compared to one with 25 mm height stiffener, and also using three and five stiffeners significantly reduces that displacement for the clamped support conditions. Moreover, these results show that increasing of the height(s) of one as well as five stiffener(s) from 25 mm to 50, 75 and 100 mm yields 18%, 22% and 24% as well as 52%, 59% and 61%, reduction in the displacement value, respectively.

From the tabulated results, it is found that the use of one stiffener in the middle of the plate is not suitable. Placing a stiffener in the middle of the plate will increase the relative percentages of displacement in the middle of the plate. Use of the five stiffeners, reduces the relative percentage of displacement in the plate, and this is found to be the best case with minimal steel material compared to the employment of one and three stiffeners. It is observed that the amount of displacement for a plate with a rectangular stiffener has increased from 5.3% to 11% relative to an unstiffened case. In case of three stiffeners, the plate displacement

| Sample | \( \psi \) | \( \zeta \) |
|--------|--------|--------|
| 25F1   | 2.5    | -16    |
| 25F3   | 7.5    | -62.2  |
| 25F5   | 12.5   | -31.2  |
| 50F1   | 5      | -82    |
| 50F3   | 15     | 11.6   |
| 50F5   | 25     | -35.2  |
| 75F1   | 7.5    | -84.6  |
| 75F3   | 15     | 12     |
| 75F5   | 22.5   | -37    |
| 100F1  | 10     | -85.4  |
| 100F3  | 30     | -37    |
| 100F5  | 50     | -85.4  |

**Table 2** Assessment of effect of number of stiffeners with different heights on the maximum displacement of the plate.

**Table 3** Assessment of variations in the plate’s cross-section and displacement.
decreases from 16% to 36% and for five stiffeners from 62% to 85%. Additionally, increasing the number of stiffeners from one to three augments the area between 7.5% and 30% for stiffeners with different heights. Also, increasing this number from three to five results in an area increase between 2.5% and 10%. In case of use of one stiffener relative to an unstiffened case, the area increases from 2.5% to 10%; however, it is noted that the plate displacement also increases in this case. On this basis, application of only one stiffener in the middle of the plate is not recommended for reinforcement of plates.

4. Conclusion

The reported numerical study focused on the serviceability performance of unstiffened and stiffened steel plates. The number and height of stiffeners were considered as two key parameters in this study. The current research showed that, for instance, application of only one stiffener in the middle of a plate for reinforcement purposes and also increase of height of a longitudinal stiffener may result in unfavorable behavior of stiffened plates. Overall, efficient stiffening and detailing of thin plates can improve the structural behavior and performance of such commonly-used elements, which despite the proliferation of respective reported research still requires detailed investigations.

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