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Article

Finite element structural analysis of simply supported solid and stiffened plates: A comparative study

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Abstract: A structure's form and shape influence how it behaves when loaded. This was achieved by contrasting the stiffened plate's performance with that of a solid plate made of the same material and volume. The results have demonstrated that bending stress in stiffened plates is decreased when a solid plate of the same material and volume is transformed into a stiffened plate. Because stiffened plates have a higher strength to weight ratio than solid plates, this supports the recommendation of stiffened plates for a variety of technical applications. In order to determine the impact of stiffener orientation on bending stress reduction in stiffened plates, additional investigations were carried out on a number of plates. An investigation was carried out to determine the ideal stiffener angle in a stiffened plate that could offer the least amount of stress. The current work offers insightful information about particular stiffened plate design characteristics that can be used in a variety of engineering contexts.

Keywords: stiffened plate; solid plate; stiffeners; orientation; finite element method

1. Introduction

In the fields of naval, aircraft, buildings, bridges, and vehicle transportation engineering, key structural elements like beams, plates, and their interconnected forms are widely analyzed. Various studies have applied different methodologies to explore the behavior of these elements. Langley et al. [1] utilized Statistical Energy Analysis (SEA) to investigate how periodically stiffened plates transmit vibration energy, specifically focusing on how the distance between stiffeners affects this energy transmission. Similarly, Bercin [2] employed both the direct-dynamic stiffness approach and SEA to study the flexural energy transfer in stiffened plates, considering factors like rotational inertia and shear distortion. Lin et al. [3] also applied the SEA method to analyze L-shaped plates with simply supported boundaries, estimating energy flow under specific force and moment excitations.

Research on stiffened plates has also been explored through static loading scenarios. For instance, Ghavami [4] conducted experimental studies to evaluate how longitudinal stiffener cross-sections and spacing influence buckling behavior and the maximum collapse load in stiffened steel plates under uniform axial loads. Here, test results were compared with different design codes which provided valuable insights into improving the accuracy of structural behavior predictions. Similarly, Hu and Jiang [5] performed full-scale tests and finite element simulations to examine the plastic post-buckling behavior of stiffened panels, enhancing our understanding of load-carrying capacity under practical loading conditions.

Dynamic approaches have been applied extensively in stiffened plate research, especially in terms of vibration and impact response. Pany et al. [6–9] leveraged the finite element (FE) method to explore wave propagation and vibration characteristics of line-supported plate and shell structures. In another dynamic analysis, Park et al. [10] applied the Flexural Stiffness Index (FSI) to optimize the design of corrugated core panels for durability under impact forces. Ke et al. [11] focused on the impact resistance of corrugated core sandwich panels within ship structures, analyzing mechanical properties under both static and dynamic loading conditions. The analyses of stiffened plates by finite element method were reported by [12–15]. Buckling analysis of these plates has been explored through both conventional and super finite element approaches, employing Mindlin plate theory and Timoshenko beam theory for modeling in [16]. Finite strip methods were also reported by [17–20]. The bending response of isotropic rectangular plates subjected to diverse loading scenarios is analyzed using MATLAB and the commercial FEM software ANSYS, incorporating Classical Plate Theory and plane stress assumptions in [21]. Additionally, [22] examines the performance of stiffened plates composed of different materials, including steel, unidirectional composite material in single-ply form, and laminated composites with five plies, highlighting the versatility of these structures in various applications.

Post-tensioned concrete bridge [23], tall RCC buildings [24], beam-column connections [25], bamboo-reinforced composite concrete [26] are just a few structural examples where beams and stiffened plate are important in design. Several studies have turned to FEA and mathematical modeling to explore complex behaviors in stiffened plates. Tanaka and Endo [27] proposed a method that combined elastic large deformation analysis with rigid-plastic analysis to assess local buckling and collapse behavior in stiffened plates with flat bar stiffeners. This method has been validated through experimental comparisons, highlighting its effectiveness in estimating ultimate loads and post-buckling behavior. Ghavami and Khedmati [28] used FEA to simulate non-linear behaviors under axial compression, revealing strong correlations with experimental results and offering predictive capabilities for flexural and local buckling phenomena. Nguyen et al. [29] have focused on refining theories for evaluating static behaviors in functionally graded plates, while others have looked at the role of stiffener angles in enhancing the load-bearing capacity of stiffened plates.

The present study aims in exploring the effect of shape and form of a structure in its behavior under loads. Research has shown that converting a solid plate into a stiffened plate of the same material and volume can significantly reduce bending stress. By carefully examining interactions between flanges and stiffeners, optimal designs can be identified to minimize stress and improve structural performance.In order to determine the effect of stiffener orientation/angles on structural performance (i.e., bending stress) in stiffened plates, additional investigations were carried out on a number of plates.

2. Analysis of stiffened plate

A stiffened plate is a plate that has stiffeners inserted between the flanges as shown in **Figure 1**. A 500 × 50 × 5000 mm steel [30] stiffened plate is analyzed under uniform pressure of 0.01 N/mm^2. It is provided in a simply supported condition with hinge support at one end and roller support at the other end. The stiffeners have a thickness of 1 mm.

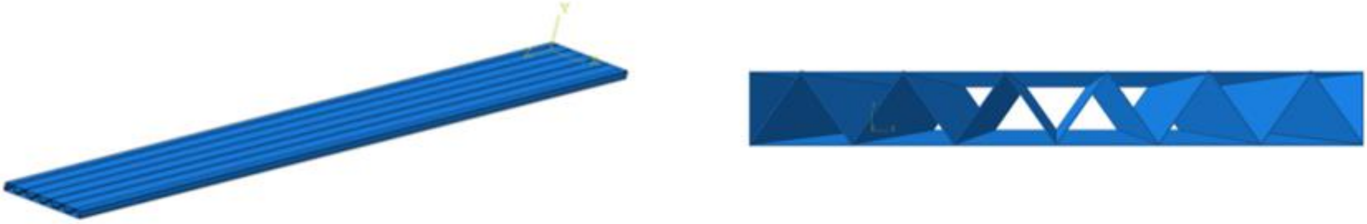


Figure 1. Stiffened plate.

2.1. Numerical simulation of stiffened plate in abaqus [12]

Abaqus software is used to model and simulate a stiffened plate, as illustrated in **Figure 2**, in order to investigate how a plate's form and shape impact its structural performance. **Figure 3** illustrates the cross section.

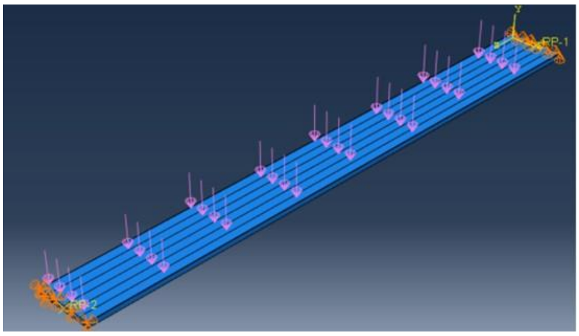


Figure 2. Stiffened plate modelled in Abaqus.

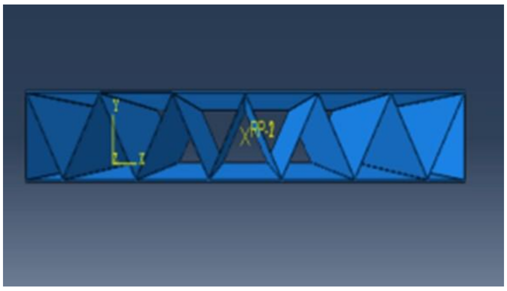


Figure 3. Cross section of the stiffened plate.

Figure 4 shows the bending stress results that were derived from Abaqus. The determined bending stress is 189.4 N/mm^2. It is evident from the research that the plate's flanges bear the majority of the bending load.

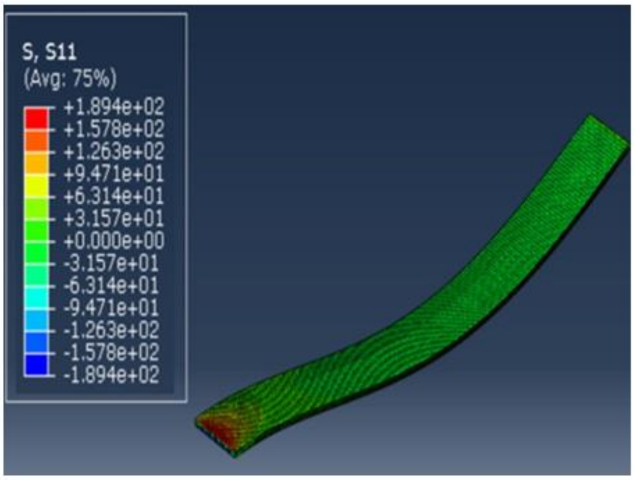


Figure 4. Bending stress of stiffened plate.

2.2. Analytical solution [31]

The accuracy of the findings obtained by the Abaqus program is verified by analytical solutions to the problems.

Span of the plate, L = 5000 mm Width of the plate, b = 500 mm

Depth of the plate, d = 50 mm

Load, $W = 0.01\text{N/mm}^2 = 0.01 \times 5000 = 5$ N/mm

Modulus of elasticity, $E = 2 \times 10^5\ \text{N/mm}^2$

Moment of inertia, $I = \frac{500\ x\ 50^3}{12} – \frac{24\ x\ 44.14\ x\ 47^3}{36} = 2153168.52\ \text{mm}^4$

Bending stress is evaluated from bending equation,

$$\frac{\text{M}}{I} = \frac{\text{f}}{y} = \frac{\text{E}}{R}$$

Maximum moment, M is obtained as 15625000Nmm and bending stress, f is found out as 181 N/mm^2

2.3. Comparison of abaqus FE results with analytical solutions

Using an analytical solution, the results of the examination of stiffened plates performed with Abaqus software are compared, and the percentage error is computed. **Table 1** tabulates the % error computation. The model is validated when the computed percentage error is less than 5%.

Table 1. Comparison of results for stiffened plates.

Structural parameter	Abaqus	Analytical	Percentage Error (%)
Bending stress (N/mm^2)	189.4	181	4.64

3. Analysis of solid plate

Under the same loading circumstances, the analysis is performed in a solid plate with the same volume and material as the stiffened plate and an equivalent depth. This provides information on how a structure’s form influences its ability to withstand load and deformation.

By equating the volume of stiffened plate with the comparable volume of solid plate, one can determine the equivalent depth of solid plate.

Volume of the stiffened plate is obtained as 0.009242 m^3.

Volume of solid plate = $5000 \times 500 \times t$

where t is the depth of solid plate

$5000 \times 500 \times t = 0.009242$

By solving the equation, equivalent depth of solid plate = 3.7 mm

3.1. Numerical simulation of solid plate

Using Abaqus software, a 500 × 3.7 × 5000 solid plate is modeled and examined to determine the maximum bending stress. **Figure 5** depicts a solid plate that has been modelled in Abaqus. **Figure 6** depicts the bending stress results that were obtained.

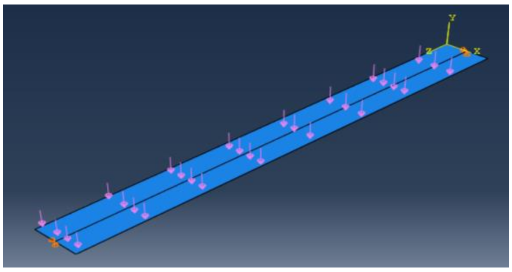


Figure 5. Finite element model of solid plate.

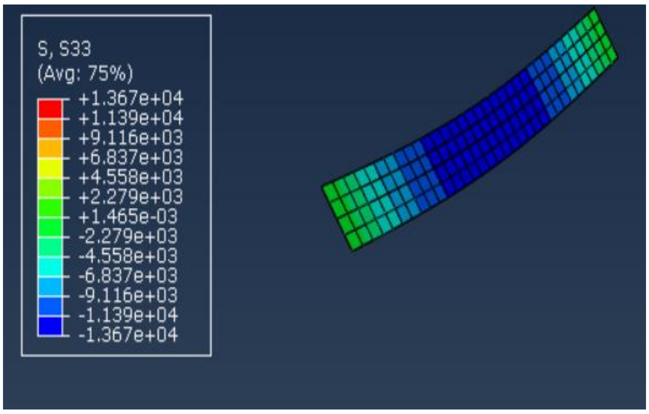


Figure 6. Bending stress (MPa) of solid plate.

3.2. Analytical solution

Maximum moment and bending stress is found out using analytical equations and are obtained as 15625000 Nmm and 0.137×10^5 N/mm^2 respectively.

3.3. Comparison of abaqus FE results with analytical solutions

Using analytical solution, the results of the solid plate analysis performed with Abaqus software arecompared, and the percentage error is computed. **Table 2** tabulates the % error computation. The model is validated when the computed percentage error is less than 5%.

Table 2. Comparison of results for solid plates.

Structural parameter	Abaqus	Analytical	Percentage Error (%)
Bending stress (N/mm^2)	0.136×10^5	0.137×10^5	0.73

3.4. Comparison of results for stiffened plate and solid plate

The comparison of results obtained for bending stress (MPa) in the stiffened plate and solid plate is tabulated in **Table 3**.

Table 3. Comparison of results for stiffened plate and solid plate.

Structural parameter	Stiffened Plate	Solid Plate
Bending stress (N/mm^2)	189.4	0.136×10^5

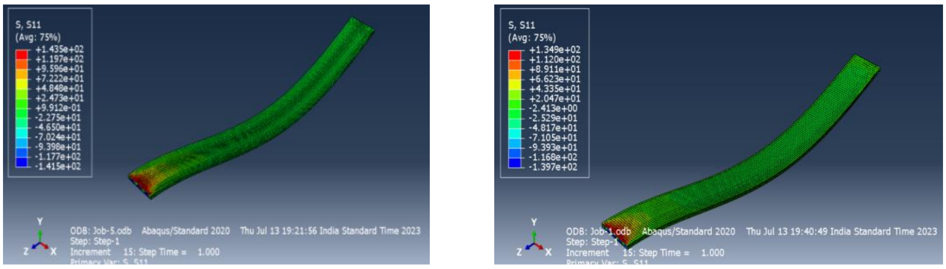
Ratio of bending stress of solid plate and stiffened plate is 71.8. So, there is a 71.8 reduction in bending stress when a solid plate is converted into a stiffened plate with the same material and volume. This is because stiffeners lessen the stress under load through distribution of load across the structure and stiffened plates have a higher strength to weight ratio than solid plates. This inference supports the recommendation of stiffened plates for a variety of technical applications.

4. Effect of angle of stiffeners on structural performance

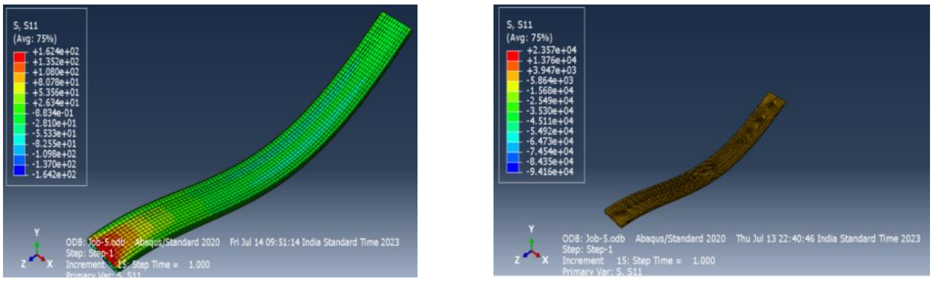
In order to determine how the stiffeners' angle affects the stiffened plate's performance, the study varies the stiffeners' angle. The study also attempts to determine the ideal stiffener angle that yields the best results under loading circumstances. Analysis of stiffened plates is done with the stiffeners angled at 30, 40, 50, and 60 degrees. It is noteworthy that the study does not include plates with stiffeners positioned at an angle greater than 60° because failure occurs when stiffeners are oriented beyond an angle of 60°.

Variation of bending stress of stiffened plate with angle of stiffeners

The bending stress of a stiffened plate is analyzed as the stiffeners' angles are changed. **Figure 7** displays the bending stress values of a stiffened plate with stiffeners positioned at 30°, 40°, 50°, and 60°. The bending stress variation with stiffener angle is depicted in **Figure 8**. According to the results, bending stress shows a decreasing trend until it reaches an optimal value, after which it begins to grow. However, the graph does not include the value of 60° because, in this case, the plate's bending stress is greater than its strength (23570 N/mm^2)



(a) **(b)**



(c) **(d)**

Figure 7. Bending stress of stiffened plate with stiffeners at various angles **(a)**30° ;**(b)** 40°**;(c)** 50°; **(d)** 60°.

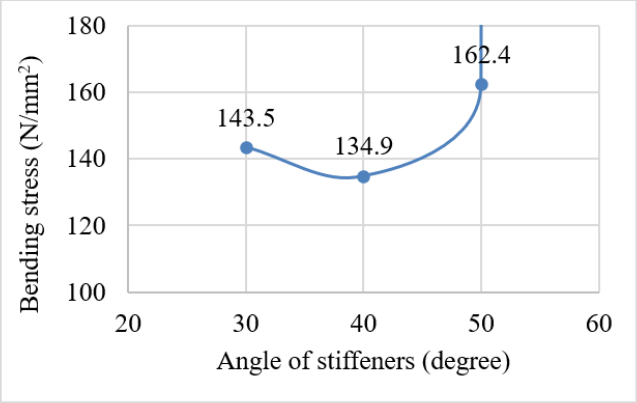
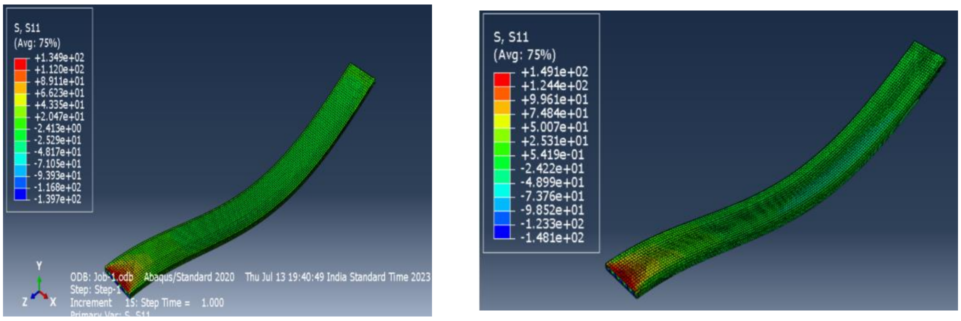


Figure 8. Variation of bending stress with angle of stiffeners.

5. Optimal angle of stiffeners in stiffened plate

The FE analysis of stiffened plate with angle of stiffeners oriented at 30°, 40°, 50°and 60° are performed and results are reported. To conduct a comprehensive analysis which enable a better assessment of optimal angle of stiffeners, further analysis is done on stiffened plate with angle of stiffeners between 40^0 and 50^0, incremented by 2°,until an upward trend in bending stress is observed. Two trails conducted at 42° and 44° and results for bending stress of stiffened plate with angle of stiffeners at 42° and 44°are shown in **Figure 9a,b** respectively. At a stiffener angle of 42°, the plate undergoes a bending stress of 134.5 N/mm^2, which increases to 149.1 N/mm^2 when the angle of stiffener is increased to 44°.



(a) **(b)**

Figure 9. Bending stress of stiffened plate with stiffeners at an angle of **(a)** 42°; **(b)** 44°.

Figure 10 shows the variation of stress of stiffened plate with angle of stiffeners. Notably, the graph excludes the case of stiffened plate with stiffeners oriented at 60° as the plate fails under this condition. The graph reveals that the plate demonstrates the lowest values of stress at an angle of 42°. Therefore, it can be concluded that the optimal angle of stiffeners, which offers improved performance under load is 42°.

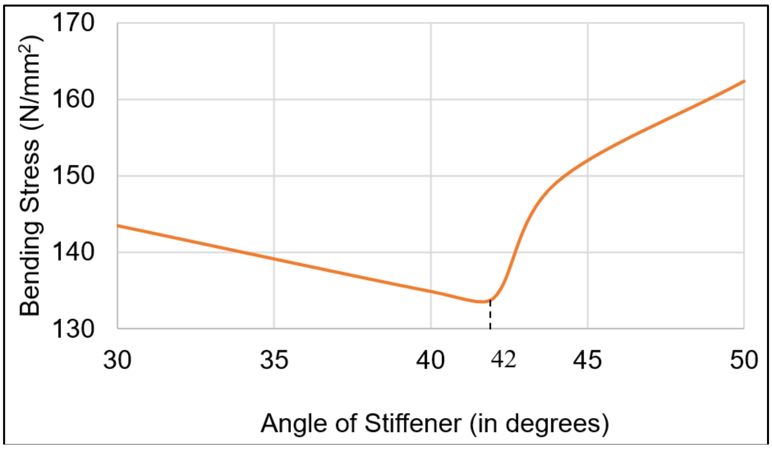


Figure 10. Graph between angle of stiffeners and bending stress.

6. Conclusions

In conclusion, this study signifies the consideration of form and shape in the design of a structure alongside its material properties in order to improve its structural performance. The key findings from the study can be summarized as follows:

1) The form and shape of a structure plays an important role in its ability to withstand external loads.
2) The transformation of a solid plate into a stiffened plate of identical material and volume results in reduction of bending stress (by a factor of 71.8) through improvement in load distribution. This strengthens the recommendation of stiffened plates for various engineering applications as the strength to weight ratio of stiffened plate is more than that of a solid plate.
3) The angle of stiffeners in a stiffened plate can be varied between 30° and 50°, with 42° being identified as the optimum value which can exhibit minimum stress in the plate through effective load distribution.

The work provides valuable insights into specific design parameters for stiffened plates, which can be applied in various engineering applications. Further studies can be conducted to delve deeper into enhancing the performance of stiffened plates by varying other design parameters, such as the depth of the sheet. Additionally, in the present work linear finite element (FE) analysis is performed. More realistic nonlinear FE analysis will give better design results of stiffened plates.

Author contributions: Conceptualization, KS and CP; methodology, KS and CP; software, KS; validation, KS; formal analysis, KS; investigation, KS; resources, KS; data curation, KS; writing—original draft preparation, KS; writing—review and editing, CP; visualization, KS; supervision, CP; project administration, KS and CP. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

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