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Mechanical Behavior of Composite Girders with Corrugated Steel Webs Based on ABAQUS

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ABSTRACT

This study evaluates the mechanical performance of composite girders with corrugated steel webs via finite element modeling in ABAQUS. Utilizing corrugated steel webs enhances structural efficiency and material economy. The research delves into shear-bending interactions, analyzing load capacity, deflection trends, and failure mechanisms. ABAQUS simulations provide insights for design optimization of these girders in engineering contexts. The findings advance understanding of composite girders with corrugated webs, fostering more effective and sustainable construction practices. The investigation focuses on using corrugated plates to bolster the shear zones in plate girders. theoretical analyses of girders with corrugated web plates demonstrate their shear zone reinforcement capabilities. Different thickness of trapezoidal corrugated steel webs in girder specimens (4, 8, 12, 16, 20 and 24 mm) underwent two-point load testing to study the corrugation's interaction with the girders. Trapezoidal patterned corrugated web specimens against one control beam shows corrugation's significant impact on girder stability, enhancing ultimate load capacity and delaying buckling. A numerical analysis using confirmed the corrugated web's role in increasing buckling resistance.

1. INTRODUCTION

A Composite girder with corrugated steel webs represents a unique and promising structural system that combines the strength and stability of steel with the lightness and versatility of composite materials. Understanding their mechanical behavior is crucial for their successful application in engineering and construction. The structural engineering field has seen significant advancements in the understanding of composite girders with corrugated steel webs, a topic extensively explored by various researchers. Sayed-Ahmed's early works [1, 2] laid the foundation by discussing lateral torsion-flexure buckling and design principles of steel I-girders with corrugated webs. Yi et al. [3] and Hassanein and Kharoob [4], provided insights into the interactive behavior of shear buckling and trapezoidally corrugated webs.

The evolution of these concepts was evident in Jiang et al.'s [5] exploration of prestressed concrete girder bridges, integrating corrugated steel webs to enhance performance. The buckling behavior, particularly flange buckling, was empirically studied by Jáger et al. [6], while Elkawas et al. [7, 8] extended this to lateral-torsional buckling strength, utilizing both experimental and numerical modeling techniques.

Riahi et al. [9] contributed to the analytical discourse with a shear buckling analysis that compared flat and corrugated webs, a comparison that was mirrored in the experimental and theoretical arenas by He et al. [10], exploring structural performance in prefabricated composite box girders. Yang et al. [11] delved into the dynamic aspects of composite trough girders, providing a theoretical and numerical study that addressed the challenges of modeling such dynamic characteristics.

Wang et al. [12] focused on the criticality of elastic shear buckling stress in large-scale corrugated webs, while Bärnkopf, et al. [13] introduced a deterministic and stochastic approach to analyzing lateral-torsional buckling resistance. The intricacies of loading over horizontal and inclined folds in corrugated web steel beams were examined by Elamary et al. [14], contributing to a nuanced understanding of load distribution.

Prefabrication emerged as a theme [15], which discussed the load-bearing capacity of steel beams with profiled sheet webs. Inaam and Upadhyay [16] identified an "accordion effect" in bridge girders with corrugated webs, highlighting the geometric complexities of corrugated structures. The dynamism of composite girders was further studied by Kong et al. [17], emphasizing the importance of corrugated webs in dynamic behavior.

Morkhade and Gupta [18] and Patil [19] employed parametric studies and finite element analysis, respectively, to study trapezoidal corrugated web beams, enhancing the computational modeling strategies for these structural elements. Al-Dhalimy and Ammash [20] investigated the effect of shear span on the behavior of steel girders, while Amani et al. [21] addressed the imperfection sensitivity of plastic shear buckling behavior in corrugated web beams.

Hamza and Muhaisin [22], Hlal and Al-Emrani [23], and Jiang et al. [24] contributed to the empirical evidence base through experimental tests and numerical analyses of various girder designs. Kollár [25] and Tian [26] examined the stability behavior under extreme conditions, such as fire, adding to the safety considerations in design.

The research trajectory includes the estimation of patch-loading resistance [27], evaluation of shear strength [28], assessment of load-carrying capacity [29], fatigue performance [30], and local shear buckling [31], each adding layers of complexity to the understanding of corrugated web girders. These studies, along with those examining the efficiency of web cutouts [32], the design of shear walls [33], and shear failure mechanisms [34], represent a rich tapestry of research that collectively advances the state of knowledge in the design and application of corrugated web steel beams in modern engineering. Many studies provided characteristics of shear strength evaluation of the structural components [35-37]. For improving accuracy, Chai et al. [39], modified calculation traditional method for calculation shear stress in girder bridges with corrugated steel webs. The shear behavior investigated by Yuan et al. [40], for bolted steel girders that have trapezoidal corrugated webs. Zha et al. [41] studied experimentally the behavior of flexural of composite beams with corrugated steel webs. Calculating the flexural capacity done by Zha et al. [42] used a new method for composite girders with corrugated steel webs. Zhou and Wang [43] investigated the performance of prismatic girders in concrete with corrugated steel webs, the shear behavior and the flexural performance explored by Zhou and Peng [44], Zhao et al. [45] and Zhao et al. [46] for prismatic and tapered prestressed concrete girders with corrugated steel webs at different conditions.

In this work ABAQUS simulations using for analysis the corrugated web interface, and their mechanical properties. This understanding is essential for accurate predictive modeling. Composite girders often exhibit nonlinear behavior under loading conditions. ABAQUS simulations enable the modeling of complex nonlinear phenomena such as material yielding, large deformations, and stress redistribution. This provides valuable insights into the girder's structural response under various loading scenarios. The buckling behavior of composite girders is a critical concern, and ABAQUS simulations can be used to assess their buckling resistance under different loading and boundary conditions. This knowledge is crucial for designing structures that are both efficient and safe.

2. SIMULATION

Simulating the mechanical behavior of composite girders with corrugated steel webs based on ABAQUS involves several steps as show in Figure 1 and Table 1 provides parameters for a simulation, related to the structural analysis of a corrugated steel girder or similar component the number of corrugations in the web of the girder, in this case, there are 10 corrugations. The total vertical dimension of the girder or the height of the web is 1000 mm (millimeters).

The horizontal span of the girder or the width of the web is 400 mm. The modulus of elasticity for the steel used is 210,000 MPa, 0.3 Poisson ratio, a 360 MPa, beyond this point, the steel will not return to its original shape when the load is removed. Materials properties assume homogenous.

Table 1. Simulation conditions

Conditions	
Number of waves	10
Depth	1000mm
width	400mm
Material	Steel
Young modulus	210000Mpa
Poisson ratio	0.3
Yield strength	360
Elastic perfect plastic	0
Assume: Homogenous	
Flange shell and web shell, Perfect elastic plastic	

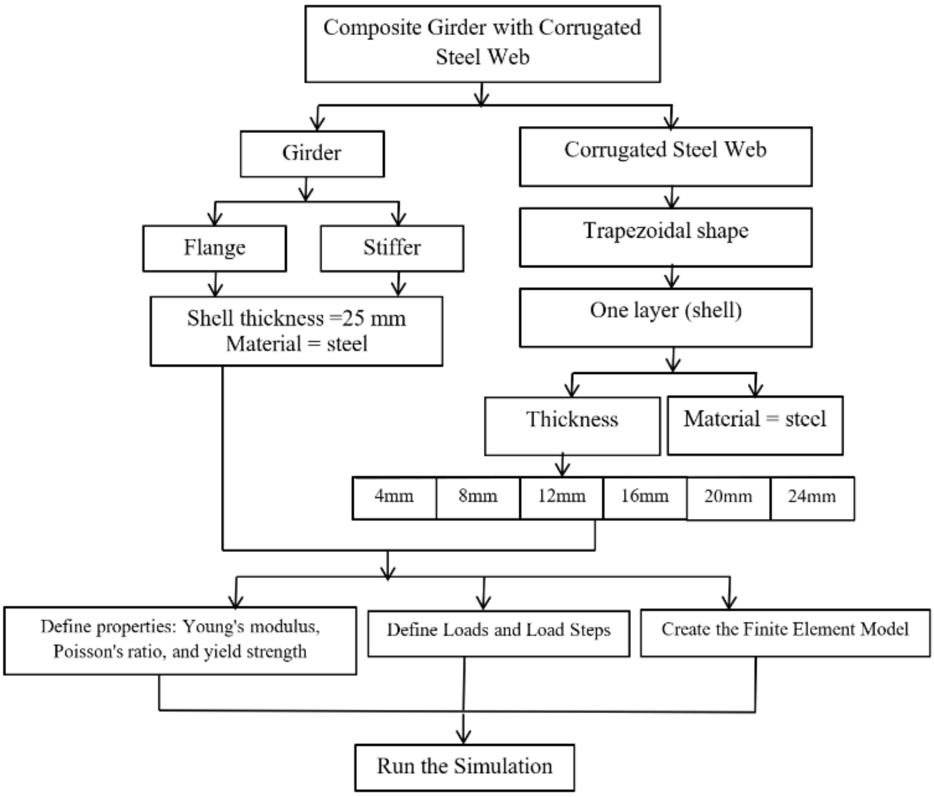
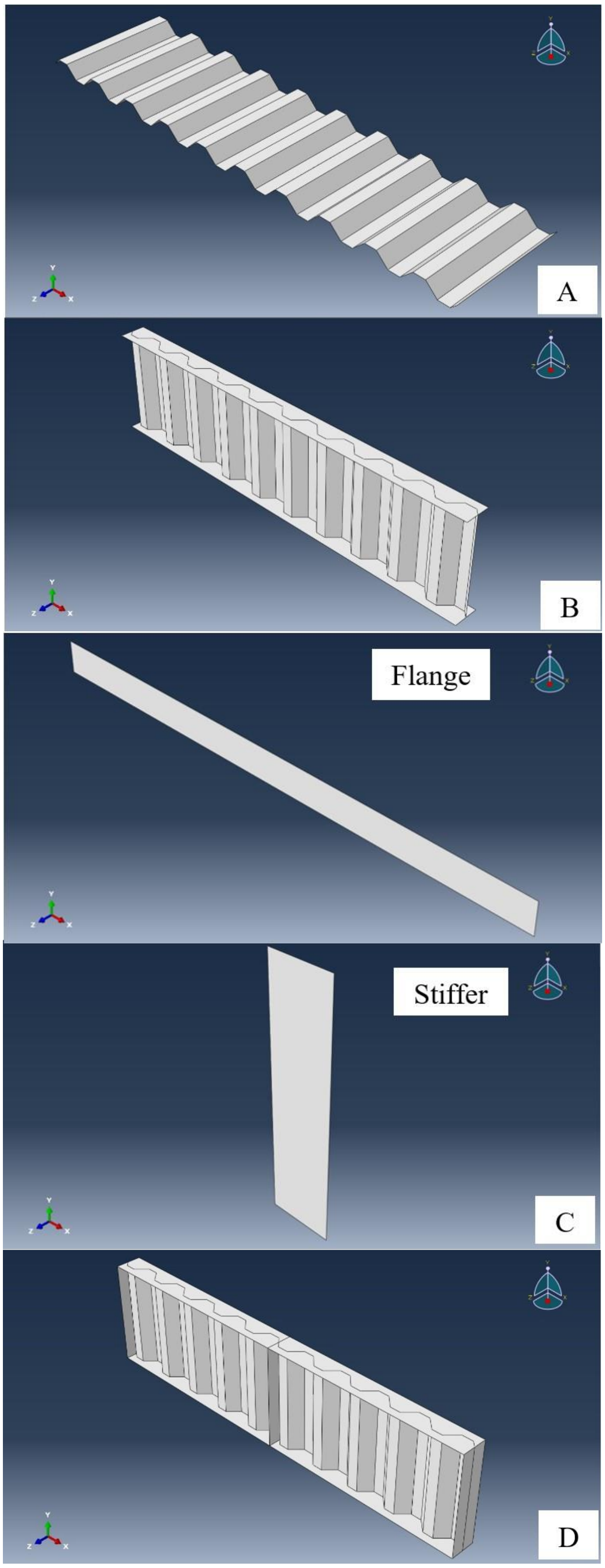


Figure 1. Chart of define model details

3. RESULTS AND DISCUSSION

Figure 2 shows the steps of simulations analysis the structural in order to study the deformation corrugated web girders under different web thickness. Figure 2a shows the corrugated web is and the girder present in Figure 2b. Figure 2c shows flange and stiffer parts. Over time, these components are subject to corrosion, leading to the final corroded web condition (Figure 2d), which impacts the structural performance, the various boundary conditions show in the Figures 2e, 2f and 2g restrict displacement along three, two, one axes respectively, (Figure 2h) shows the mesh used in the analysis of structure. Figure 3 provided the results from a series of finite element analyses showing the von Mises stress distribution in a composite girder with a corrugated steel web. Figures 3a, b, c, d, e, f corresponds to a different thickness of the web, from 4 mm to 24 mm. The color-coded representation of the von Mises stress distribution within the girder, with red indicating areas of highest stress and blue indicating areas of lowest stress. This distribution helps identify where the structure is experiencing the most and least stress under the given load conditions, As the thickness of the web increases from Figures a (4 mm) to f (24 mm), there is a noticeable change in the stress distribution patterns. Thicker webs may show less intense red areas, suggesting a reduction in maximum stress points. Figure 3 likely show that stress concentrations (areas where stress is significantly higher than the surrounding areas) occur at certain points regardless of the web thickness. These concentrations are often around geometric discontinuities such as where the corrugations meet the flanges or at sharp corners, thinner webs (Figures 3a and 3b) show higher stress concentrations, indicating that they may be more susceptible to local yielding or buckling under load. In contrast, thicker webs (Figures 3e and 3f) distribute the stress more evenly, which can be beneficial for the structural capacity of the girder, in practice, selecting the web thickness for a girder involves a trade-off between material costs and structural performance. While thicker webs improve the distribution of stress and increase the load-carrying capacity, they also add weight and material costs, direct comparison between the different thicknesses can provide valuable insights into how much the increased thickness contributes to the reduction in stress concentration. This can help in designing more efficient structures by optimizing the material thickness where it is most effective. These results could be used to optimize the girder design. Figure 3c, the web 12 mm shows a sufficient safety margin, Figure 3d increasing the thickness to 16 mm, the benefits not yield significant, depending on the structure requirements. Stress distribution in composite girders with corrugated webs shows stress concentrations high at peaks of the corrugation at the connection’s web and flanges. An initial linear elastic presents in the region of the load-deflection curves followed by a nonlinear behavior as the composite yields, and a descending curve indicating failure as in Figure 4, which shows a load - deflection curve for composite of different thicknesses (4-24) mm, the figure is critical in structural for engineering assessing of the performance component under loading.

The area under each curve (Figure 4) represents the energy absorption capacity or ductility of the girder. A larger area indicates that the girder can absorb more energy before failure, which is a desirable property in structural design. The initial slope of each curve indicates the stiffness of the girder. A steeper slope means higher stiffness, which implies less deflection for a given load. Thicker webs generally show higher peak loads (higher load-carrying capacity) and lower deflections (higher stiffness), the 24 mm web can carry more load with less deflection compared to the 4 mm web. There is a diminishing return on increasing thickness after a certain point, the difference in performance between the 20 mm and 24 mm webs might not justify the additional material cost. The Figure 4, shows that girders with thinner webs (4 mm) have significantly lower load capacities and higher deflections, which may not be acceptable for safety and serviceability criteria.



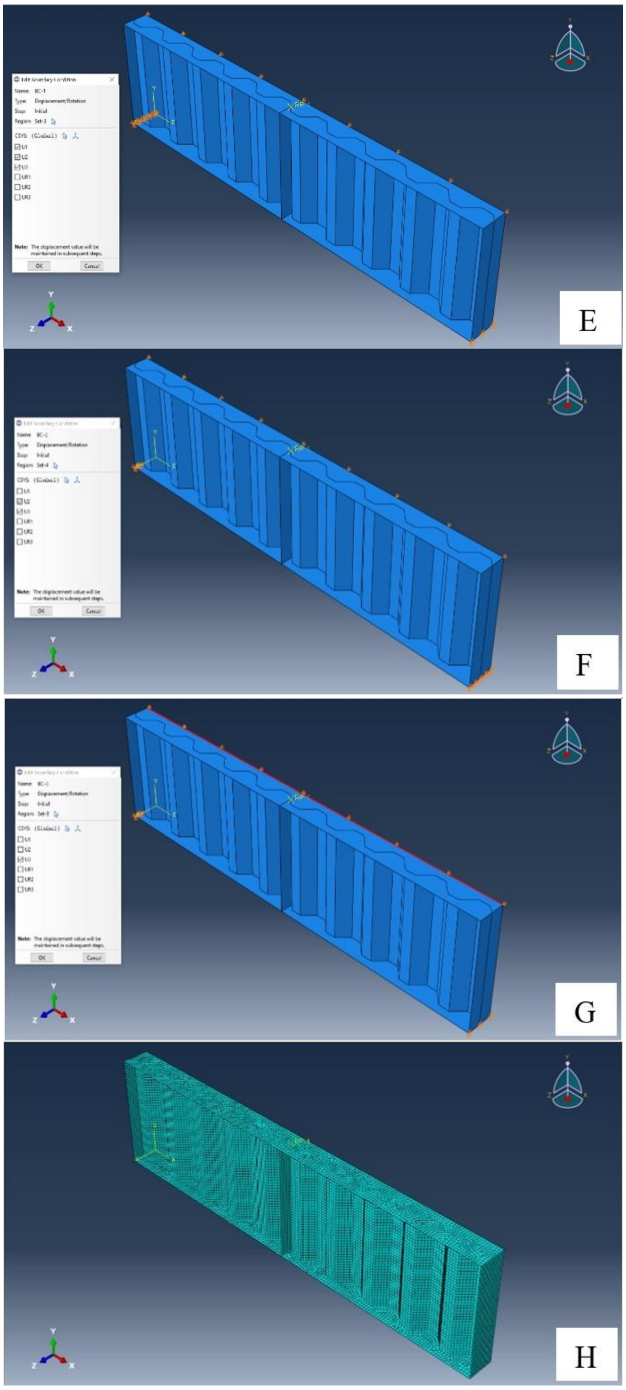
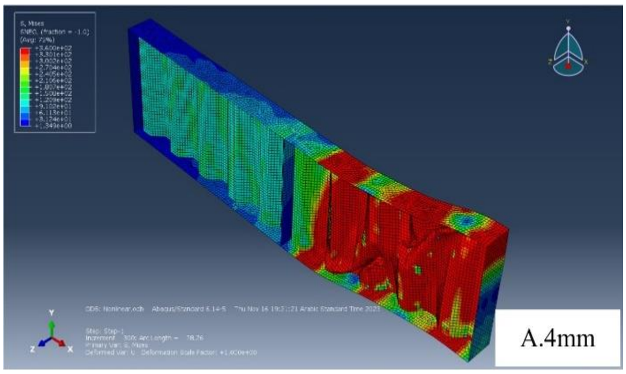


Figure 2. a. Corrugate web, b. girder, c. flange and stiffer, d. final corroded web, e. boundary condition 1 (for three axis displacement), f. boundary condition 2 (for two axis displacement), g. boundary condition 3 (for one axis displacement) and h. mesh



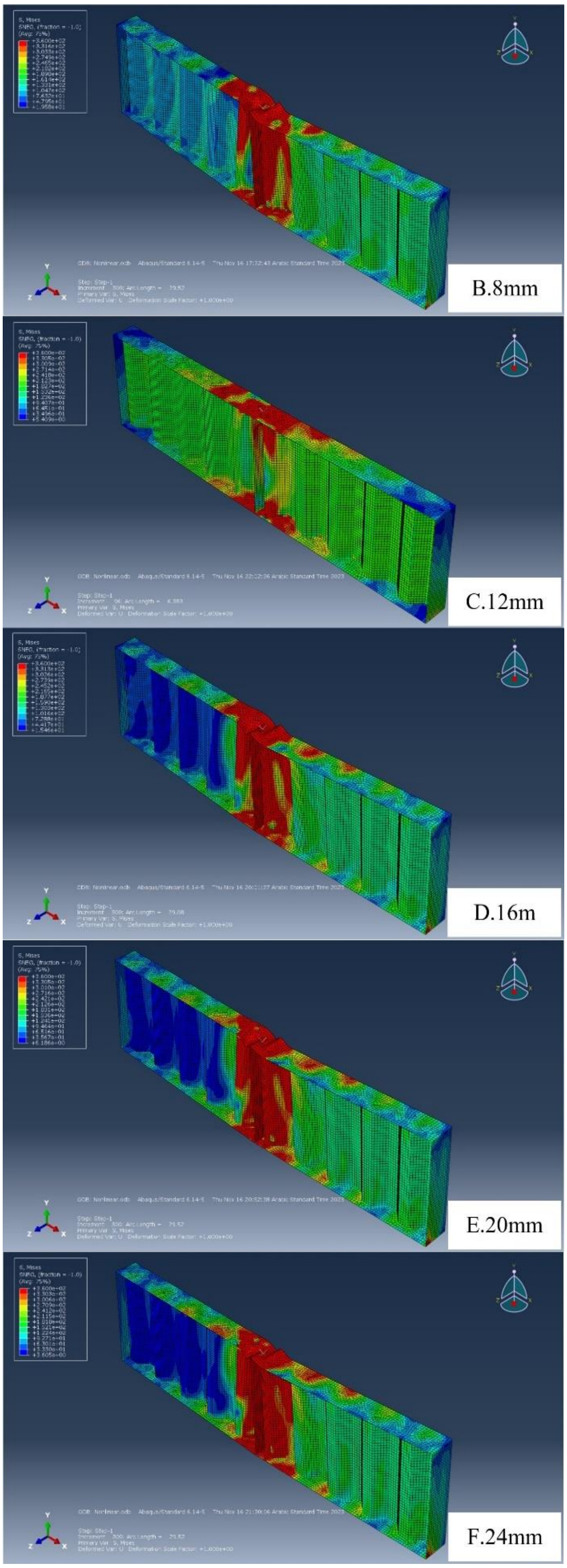


Figure 3. Stress distribution (Von-Misses) for composite girder with corrugated steel web

The 12 mm line starts with a steep gradient, indicating high initial stiffness. This means that for small loads, the deflection (or bending) of the girder is relatively small. The girder with a 12 mm web reaches its peak load capacity at a point before the curve starts to flatten out. This peak represents the maximum load that the girder can carry before it yields significantly. After the peak, the curve for the 12 mm web flattens, indicating that the material has begun to yield. The girder continues to carry load but with increasing deflection, suggesting plastic deformation.

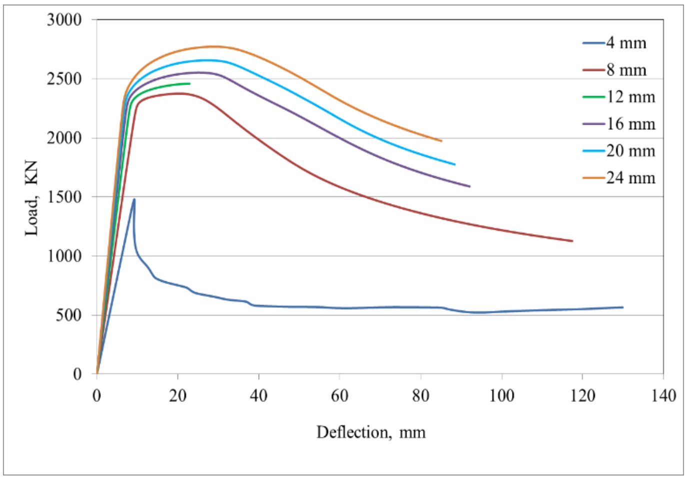


Figure 4. Load-deflection curve for composite girders with corrugated steel webs

The area under the curve represents the energy absorption before failure. For the 12 mm web, the curve extends significantly along the deflection axis after yielding, which shows ductility; the girder can undergo large deformations without a substantial decrease in load-carrying capacity.

When compared to thinner webs (like the 4 mm and 8 mm), the 12 mm web can carry a higher load and has a higher initial stiffness. However, it is less stiff and has a lower load capacity than thicker webs (like the 16 mm, 20 mm, and 24 mm). It seems to represent a mid-range option in terms of both stiffness and strength.

The chart in Figure 5, provided displays the ultimate loads for composite girders with varying thicknesses of corrugated steel webs. There is a clear trend that indicates an increase in web thickness correlates with an increase in the ultimate load capacity, up to a certain point. This suggests that thicker webs can carry more load before reaching failure. The jump in load capacity from 4 mm to 8 mm and 12 mm is quite significant. However, as the thickness continues to increase to 16 mm, 20 mm, and 24 mm, the increases in load capacity become less pronounced. This could indicate that beyond a certain thickness, the additional material does not contribute as effectively to load-bearing capacity.

The load-versus-displacement displayed in Figure 4 indicates that increasing web thickness contributes to higher load capacities. This is consistent with the conclusions of the study [47], which show that thicker webs execute better after achieving peak load.

He et al. [47] showed that steel I-girders achieve higher ultimate and yield loads (up to 4500 kN for a 12 mm web) compared to the ultimate loads of composite girders with corrugated steel webs (up to 3000 kN for a 24 mm web), as shown in Figure 5. This highlights the critical role of web thickness in enhancing structural performance across different girder types. The difference in load-carrying capacities is due to the various kinds of girders analyzed and the materials used. The present work focuses on composite girders with corrugated steel webs, which combine materials and structural forms but typically achieve lower ultimate loads (up to 3000 kN for a 24 mm web) due to their composite nature and different failure mechanisms.

Depending on the specific requirements of a project, there may be an optimal thickness that balances material efficiency and load-bearing capacity. For instance, if the load conditions do not necessitate the highest capacity, a 16 mm or 20 mm web might be the most cost-effective choice.

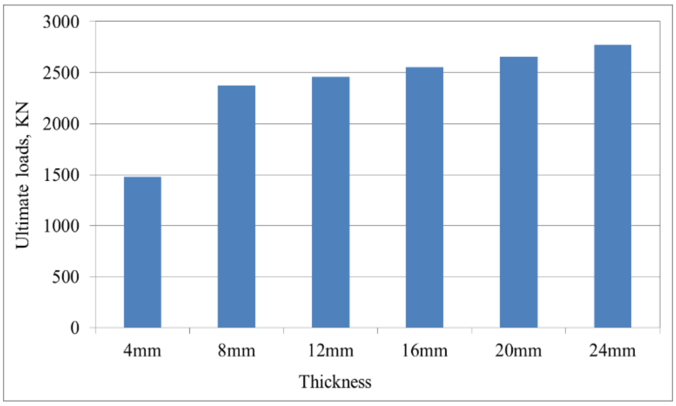


Figure 5. Ultimate loads for composite girders with different corrugated steel web thickness.

4. CONCLUSIONS

Composite girders behavior with corrugated steel webs is analysis using ABAQUS for simulation for encompassing stress distributions effect of the composite girder under different thickness and loading. From the results of simulation, the nonlinear mechanical behavior of the composite girder. which performs under the variety of web thickness and loading. In order to found the limit of deflections in serviceability considerations, to prevent damage in structural elements, the results illustrate the stress distribution in a composite with web of (4, 8, 12, 16, 20, and 24 mm) thickness, it is clear that thinner webs of 4 mm and 8 mm exhibit stress which may lead to unsuitable for high load applications, where a web thickness of 4 mm shows high stress regions, and the increasing the thickness of web to 8 mm reduces the stress. At 12 mm, stress distribution improves at 12 mm thick with fewer high stress regions. Further reduces high stress regions at 16 mm thick, showing better structural efficiency, the thickness of 12 mm and 16 mm suitable for application of moderate loads. Mostly low to moderate stress levels at 20 mm thick, which offers a balanced performance with low levels stress, producing it an adaptable choice. The best stress distribution and performance at 24 mm thick with shows minimal high stress regions.

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