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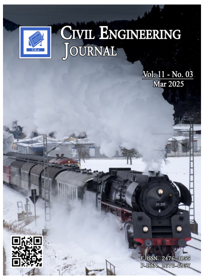

Nonlinear Finite Element Analysis of I-Steel Beam with Sinusoidal Web

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Abstract

For structural models, existing research frequently uses deterministic numerical analysis. Test findings, however, constantly point out uncertainties, especially about variables like the imposed load's amplitude, geometrical dimensions, material unpredictability, and inadequate experiential data. In response, scholars have focused more on probabilistic design models, realizing their importance for precisely forecasting structural performance. This research aims to incorporate reliability-based analysis into the numerical modeling of steel beams with sinusoidal webs. A steel welded plate beam with an I-section and a sinusoidal web has been taken into consideration in this study. The web height is 750 mm, the web thickness is 2.0 mm, the flange width is 300 mm, and the flange thickness is 5.0 mm. The beam's length, l = 1000 mm, has two 10.0 mm thick stiffeners positioned beneath the applied load to stop the flange from failing locally as a result of load concentration and end plate supports that are 5 mm thick. The commercial software application ANSYS ver. 2019 R3 has been used to perform a nonlinear finite element analysis in order to examine the failure modes and load capacities. In the first stage of this study, the changing of the amplitude/period ratio, A/P, was taken into consideration to examine the failure capacity loads and deformed shapes to optimize the amplitude/period ratio. In the second stage, the optimum amplitude/period ratio, A/P, was taken, and changing the period/span ratios, P/L, made the best use of the period/span ratios by examining the failure capacity loads and deformed forms.

Keywords: I-Steel Beam; Sinusoidal Web; Nonlinear Analysis; Amplitude/Period Ratio; Period/Span Ratio.

1. Introduction

A steel beam with a sinusoidal web is a type of structural component used in building and construction. It is a variation of a steel I-beam. Depending on the dimension of the beam and level of loading, the design and specifications of the steel I-beam mostly require the plain web to be strengthened by discrete transverse and longitudinal stiffeners. The sinusoidal web, on the other hand, could be the alternative choice to overcome the web instability and at the same time provide more rigidity and strength to the I-beam. This alternative gives a chance to resist more loading for the same span and depth and the same or even less use of material, in addition to expecting more torsional resistance compared to the standard I-beam. Steel beams with sinusoidal webs are made by folding a flat steel plate into a wavy shape, with alternating peaks and valleys along the length of the beam. This design creates a series of interconnected triangles that provide greater rigidity and strength than a straight web due to the curvature of the web and more surface area than the I-beam with a flat web. The sinusoidal shape could also reduce the weight of the beam due to a reduction in the web thickness, and that could make it easier to transport and handle during construction.

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The interlocking triangles also help to prevent the beam from buckling or bending under heavy loads, which can cause significant damage to the structure. Another advantage of the sinusoidal web design is that it provides greater stiffness than a standard I-beam. This means that the beam is less likely to deform under load, which can cause problems with the overall stability of the structure. The stiffness of the beam also makes it easier to control deflection, which is the amount of bending that occurs when the beam is loaded. The most disadvantageous aspect of the sinusoidal web is the difficulty of fabrication regarding welding the sinusoidal web to the flanges. However, the alternative of using discrete straight transverse and longitudinal stiffeners is also including additional work and issues of welding.

Elamary et al. [1] The impact of a steel top flange on the failure mechanism of a concrete-steel composite beam with a corrugated web under bending was investigated experimentally. They discovered a 12% improvement in load capacity and a 30% increase in stiffness. Zhu et al. [2] investigated the load-carrying capacity and hysteresis behavior of corrugated web beams under cyclic and monotonic loads. Additionally, the failure mechanisms were examined. Dubina et al. [3] conducted tests on trapezoidal web components that were fastened with self-drilling screws. The employment of both seam fasteners and flange-web connectors is the optimal connection suggested in the study. Eurocode 3 EN1993-1-5 [4] embraced the Hoeglund model [5, 6], which is an expansion of a previous theory based on the mechanism of rotational stress fields. According to experimental results, the model provides conservative shear strength results for thin web plates by taking into account plate girders with transverse stiffeners. Jiaoa et al. [7] investigated how geometry affected composite wood beams with sinusoidally corrugated webs' buckling capacity. There is a noticeable increase in buckling load (at least 17.7%) between I-beams with sinusoidal and flat webs. The effects of web thickness, girder length, and girder depth on the ultimate load capacity of sinusoidal I-beams are assessed using a sensitivity study [8].

Chen & Young [9] suggested a corrugated web-connected buckling-restrained strut (CWC-BRB), a novel form of core-separated BRB. The CWC-BRB's hysteretic behavior under cyclic loading, its ultimate capacity under monotonic loading, and its elastic buckling load were all examined. With reference to EN-1993-1-5 [4], Johansson et al. [10] determined that a slenderness ratio of less than 0.25 can be used to safely attain the shear yield point. Eldib [11] offered a remedy for bridge structural girders with sinusoidal web profiles. The link between buckling stress and slenderness, as determined by FEM investigations, served as the foundation for the solution [12]. Basiński & Kowal [13, 14] and Basiński [15] noted findings indicating that in sinusoidally corrugated webs, the design shear buckling resistance indicated in the standards is overestimated. Furthermore, research has shown that the buckling resistance of beams with sinusoidal web profiles is decreased by an interaction between the local and global modes of shear instability. It was discovered that the zone of shear instability of the web moves from the connection to the stiffener in the end plate connection of precast beam elements. End stiffeners have a major impact on the buckling resistance of the web, according to studies of corrugated and flat web girders composed of individual members and shear resistance analysis.

Höglund [16] determined that at slenderness of λ (buckling length/radius of gyration) >1.08, the effect of end stiffeners on shear buckling resistance already manifests itself. The range of slenderness for sine wave corrugated web girders is $1.88 < \lambda < 7.98$. End stiffeners in corrugated web girders are typically composed of flat plates. Malik et al. [17] Four corrugation types—trapezoidal, rectangle, triangular, and octagonal—and three depths (20-30-40 mm) were used in the study's finite element analysis (FEA) to examine the impact of these factors on the performance of sandwich corrugated beams. When the punitive length of the plate was equal to its height, the tested beams performed at their best. The best kind of corrugation was rectangular, and its shape has an impact on the shear strength of the beam. Li et al. [18] investigated how corrugated beams behaved under flexural load. They created and examined FE models with a number of variables, and the results showed that variations in the span-to-depth ratio and steel yield strength have a major impact on the maximum load-carrying capacity of beams. It has been demonstrated that there is good agreement between the theoretical and numerical results. Ammash & Al-Bader's [19] the shear, flexure, and ultimate failure of corrugated steel I-girders under one-point load were investigated in this work. Ten specimens were employed, comprising trapezoidal, rectangular, and triangular corrugation types as well as a flat web. The findings revealed a 28% increase in trapezoidal corrugation beam strength along with various failure types.

Kadhim & Ammash [20] used three different shapes to examine the shear strength of concrete-filled corrugated steel I-girders. They discovered that the shear strength of corrugated girders with concrete was higher than that of those without concrete encasing. The shear strength of the steel girder filled with concrete was also affected by the corrugation shape [21-23]. Numerous experiments on corrugated plates with different corrugation orientations, forms, and stiffeners demonstrated that the parameters under study had an impact on the corrugated plates' characteristics. Manoj Kumaar et al. [24] investigated the flexural behavior of beams with flat and corrugated webs using ABAQUS software. Jumaa & Majeed [25] modeled several girder components using non-linear finite element analysis (FEA) with the Abaqus software program. They evaluated the agreement between experimental results and theoretical analysis using theoretical modeling based on previous studies. Later, they improved the model by including corrugated web structures and external stiffeners that are known to increase the web's shear tolerance. Taking advantage of the known advantages of this combination, our new model showed an 11% improvement in resistance and much higher resilience than traditional designs without stiffeners. Eurocode 3 EN1993-1-5 [4] Shear design formulae for beams with sinusoidal corrugated webs are unique to this standard. Annex D of the Eurocode provides the formula for the elastic local shear buckling stress of beams with sinusoidal corrugated webs as:

$$\tau_L = (5.34 + \frac{A_S}{ht_w})\frac{\pi^2}{12(1-\nu^2)}(\frac{2t_w}{s})^2 \quad (1)$$

where A is the amplitude of the sine wave.

It is clear from the literature above that few research studies have been done on how varying the period length and amplitude of the I-steel beam's sinusoidal web affects load capacity and failure mode geometries. Changing the period length and amplitude of the sinusoidal web of the I-steel beam can have an impact on its design and performance. The best design for an I-steel beam depends on several factors, including the target load, the span length, the type of material used, and the allowable deflection or deformation. In general, increasing the amplitude of an I" steel beam will increase its stiffness, which can be beneficial for resisting bending and buckling under heavy loads. However, increasing the amplitude too much can lead to a decrease in the beam's load-carrying capacity, as it may become more susceptible to buckling. On the other hand, changing the period of a sinusoidal web can affect its stiffness and load-carrying capacity. A shorter period will generally result in a stiffer beam, while a longer period will result in a more flexible beam and increase the risk of buckling under heavy loads.

2. The Current Case Study

In this study, a steel welded plate beam of I-section and sinusoidal web has been considered, with a web height, h_w of 750 mm, a web thickness, t_w of 2.0 mm, a flange width, b_f of 300 mm, and a flange thickness, t_f of 5.0 mm. Shear buckling may occur because the web slenderness ratio is $h_w/t_w = 750/2.0 = 375 > 260$ as per AISC specifications [26]. The length of the beam is l = 1000 mm with two stiffeners of 10.0 mm thickness placed under the applied load to prevent the local failure of the flange due to load concentration and 5 mm thick end plate supports as shown in Figure 1. A nonlinear finite element analysis has been carried out using the commercial software program ANSYS ver. 2019 R3 [17] to investigate the failure modes and load capacities of sinusoidal web beams. The aim of the study is to explore the effect of wave amplitude and period of sinusoidal web on deflection, failure mode, and failure load. The sequence of Nonlinear Finite Element Analysis can be briefly described by the flowchart shown in Figure 2.

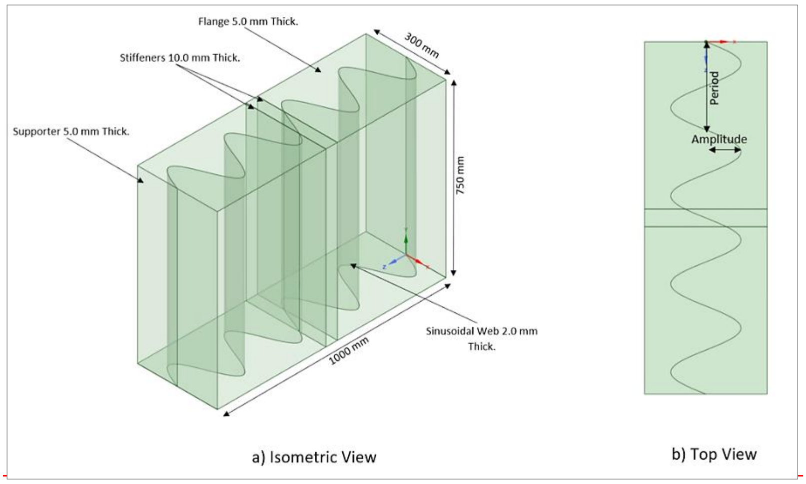

Figure 1. Geometrical Details of Model

2.1. Material Properties

The nonlinear behavior of steel has been simulated using a bi-linear elastic-perfectly-plastic stress-strain curve. The material characteristics that were employed were Young's modulus of 2×10^5 MPa, shear modulus of 7.6923×10^4 MPa, bulk modulus of 1.6667×10^5 MPa, yield stress of 265 MPa, and Poisson's ratio of 0.3. It should be noted that the construction of sinusoidal web beams and the residual stress of plate welded beams are complex issues that are not mainly discussed in the literature; as such, they are outside the purview of this investigation.

3. Finite Element Modeling

A four-node structural shell element (SHELL181) from the ANSYS ver.2019R3 library has been used in this nonlinear finite element study to investigate the failure mechanisms and load capacity. With three rotations about the x, y, and z axes and three translations in the x, y, and z directions, the element has six degrees of freedom at each node. Applications involving massive rotation, large strain nonlinearity, and the impact of distributed pressures on load stiffness are suitable for this element. Both partial and complete integration schemes are offered. The results of multiple analysis sessions utilizing mesh sizes of 100, 50, 25, and 12.5 mm showed that a mesh size of 25 mm produced adequate precision in a fair amount of analysis time, which is why it was used throughout.

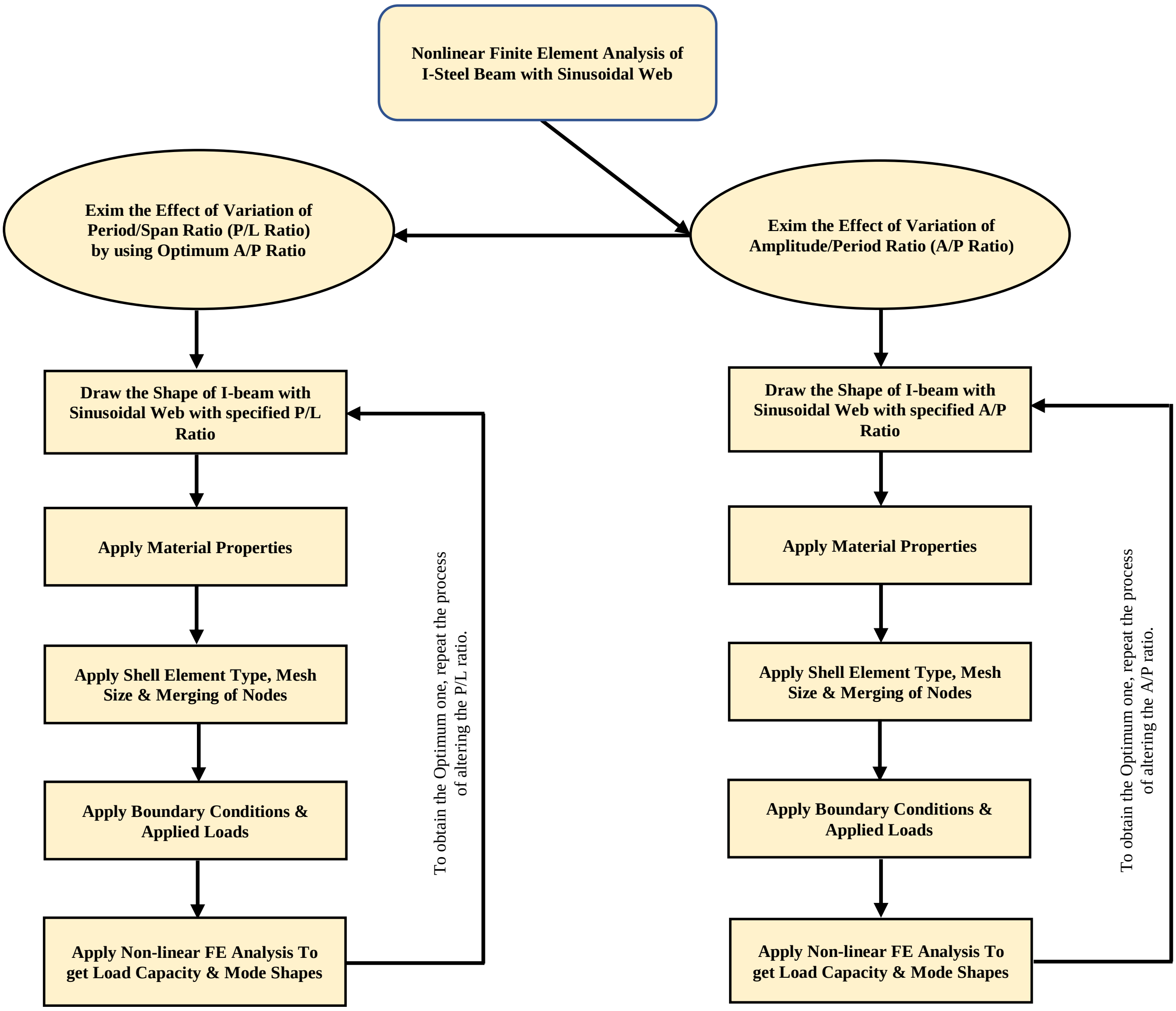

Figure 2. Nonlinear Finite Element Analysis Flow Chart

3.1. Merging of Nodes

It is feasible to merge two different entities into one when they are in the same place. For example, when joining two previously meshed regions, it could be preferable to have all the nodes move in unison across all degrees of freedom. The lower-numbered coincident node will take the place of the higher-numbered node, which will be removed. The nodes can be renumbered and merged by ANSYS based on a predetermined tolerance. Consequently, two merged nodes will be replaced by a single node. Figure 3 displays the finite element mesh.

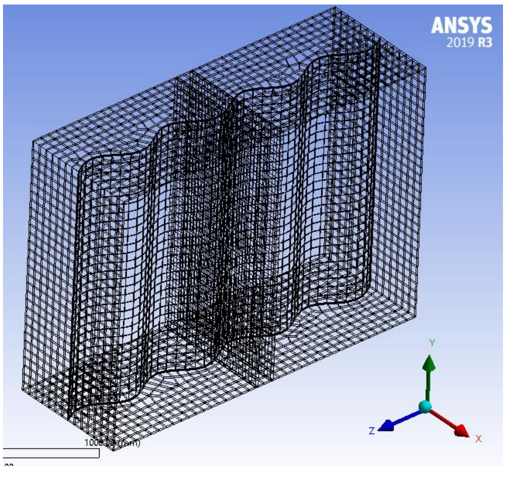

Figure 3. Finite Element Mesh Size and merging of coincident nodes

3.2. Boundary Conditions and Load Application

In ANSYS, loads can be applied to the solid model (on keypoints, lines, and regions) or the finite element model (on nodes and elements). The specification of a load at a keypoint or node is one example; nevertheless, the FE model needs to receive this information. Additionally, nodes, element faces, lines, and areas that will subsequently be transferred to the finite element model can be used to directly specify surface loads and pressure. Regardless of how they are given, the solver assumes that all loads will be applied to the finite element model. As a result, at the beginning of a solution, the program automatically transfers any loads set on the solid model to the nodes and elements.

Both ends were kept as fixed supports for the sake of this investigation. A fixed end support is more difficult to produce in real-world tests than a pinned end support, but it is considerably easier to represent for numerical models. For these supports, it is necessary to constrain all rotations (ROTX, ROTY, and ROTZ) and translations in the three directions (UX, UY, and UZ) (Figure 4). The focused load was applied in the center of the span length and dispersed over the element face area to avoid stress concentration (Figure 5).

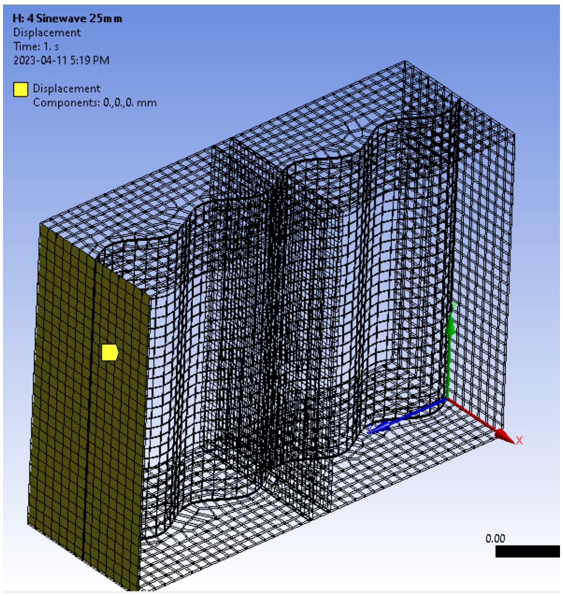

Figure 4. Fixed End Support

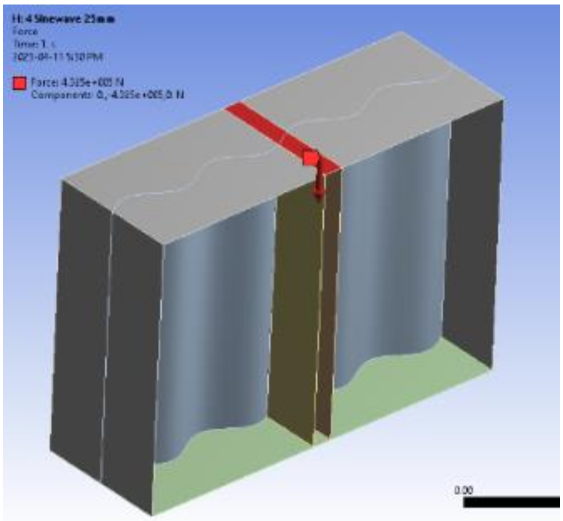

Figure 5. Finite Element Modelling of Concentrated Load

3.3. Non-linear ANSYS Analysis

Element type and material attributes with nonlinear features (i.e., nonlinear stress-strain curves) were carefully chosen before beginning nonlinear analysis in ANSYS. When buckling starts can be predicted from the ANSYS findings, but if the structure can still support the load, the solution might keep convergent. Before the solution phase for the nonlinear analysis can start, a number of solution parameters need to be established. The following factors should be taken into account by basic solution options:

- Allowing for large static displacements will incorporate the effects of large deflection, or nonlinear geometry, into the results.
- Check to see if automatic time stepping is turned on. To achieve convergence, ANSYS selects the appropriate load step sizes using an automated time step. It takes patience, but lowering the step size usually improves accuracy. The automatic time step feature will select a suitable balance and use bisection to adjust load steps as the solution evolves to ensure convergence.
- If there are n sub-steps, the first sub-step is set to $1/n^{th}$ of the overall load.
- The program will end when the maximum number of sub-steps is m if the solution does not converge after m steps.
- The bare minimum is one sub-step (as shown in Figure 6).
- All of the solution items are included in a results file. It is possible to write out only specific findings that are of interest because a large model may result in a large results file size.
- To save all sub-step outcomes, note down each sub-step's frequency.
- Making sure that the solution output is force convergence. This option aids in the convergence of the Newton-Raphson solver (as shown in Figure 7).
- Verifying that the "Maximum Number of Sub-Steps" and the "Maximum Number of Iterations" match.

Details of "Analysis Settings"	
Step Controls	
Number Of Steps	1.
Current Step Number	1.
Step End Time	1. s
Auto Time Stepping	On
Define By	Substeps
Initial Substeps	50.
Minimum Substeps	25.
Maximum Substeps	100.
Solver Controls	
Solver Type	Program Controlled
Weak Springs	Off
Solver Pivot Checking	Program Controlled
Large Deflection	On
Inertia Relief	Off
Rotordynamics Controls	
Restart Controls	
Nonlinear Controls	

Figure 6. Details of Analysis Settings

Details of "Solution Information"	
Solution Information	
Solution Output	Force Convergence
Newton-Raphson Residuals	0
Identify Element Violations	0
Update Interval	2.5 s
Display Points	All
FE Connection Visibility	
Activate Visibility	Yes
Display	All FE Connectors
Draw Connections Attached To	All Nodes
Line Color	Connection Type
Visible on Results	No
Line Thickness	Single
Display Type	Lines

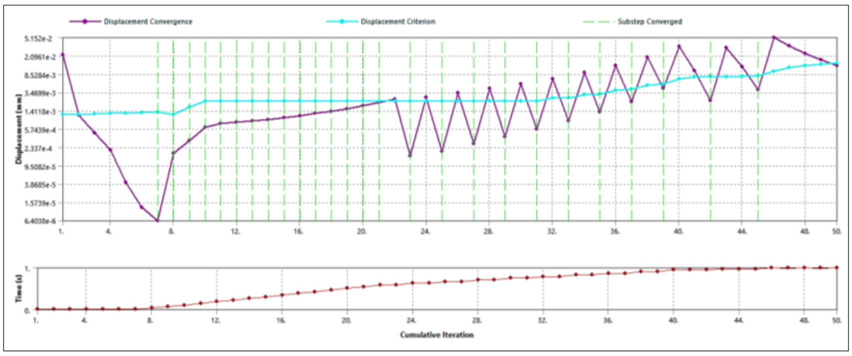

Figure 7. Details of Solution Information

3.4. Verification of Finite Element Analysis

For verification purposes, all of the current study's assumptions were applied to a model that was taken from a prior experimental study, which was then remodeled and loaded differently. The results were then compared to those of the previous study, and the degree of convergence between the two was examined. The goal of this is to determine how reliable the current study model's modeling and assumptions are.

Cserpes et al. [27], The SIN-240 beam was taken, the material properties used in prior study are different for the sinusoidal-web plate and the flange portion. The ultimate strength (f_u) and yield strength (f_y) for the flange portion are measured at 636.6 MPa and 288 MPa, respectively. On the other hand, the sinusoidal-web plate has a yield strength (fy) of 282 MPa and an ultimate strength (f_u) of 639 MPa, indicating somewhat different material characteristics. The SIN-240 beam modeling in ANSYS ver.2019 R3 [17] is displayed in Figure 8-a, which corresponds to the modeling of a previous study in Figure 8-b. The applied loads and displacements that resulted from the current study were in good agreement with those from the previous study, with a 95% agreement in Figures 8-c and 8-d. It should be mentioned that the failure models in the experimental and numerical results of the prior study and the numerical results of the current study differ because the hypotheses used in the two analyses were different (Figures 8-c and 8-d). According to the aforementioned, the modeling approach used in this study can be trusted to present the findings in a meaningful way.

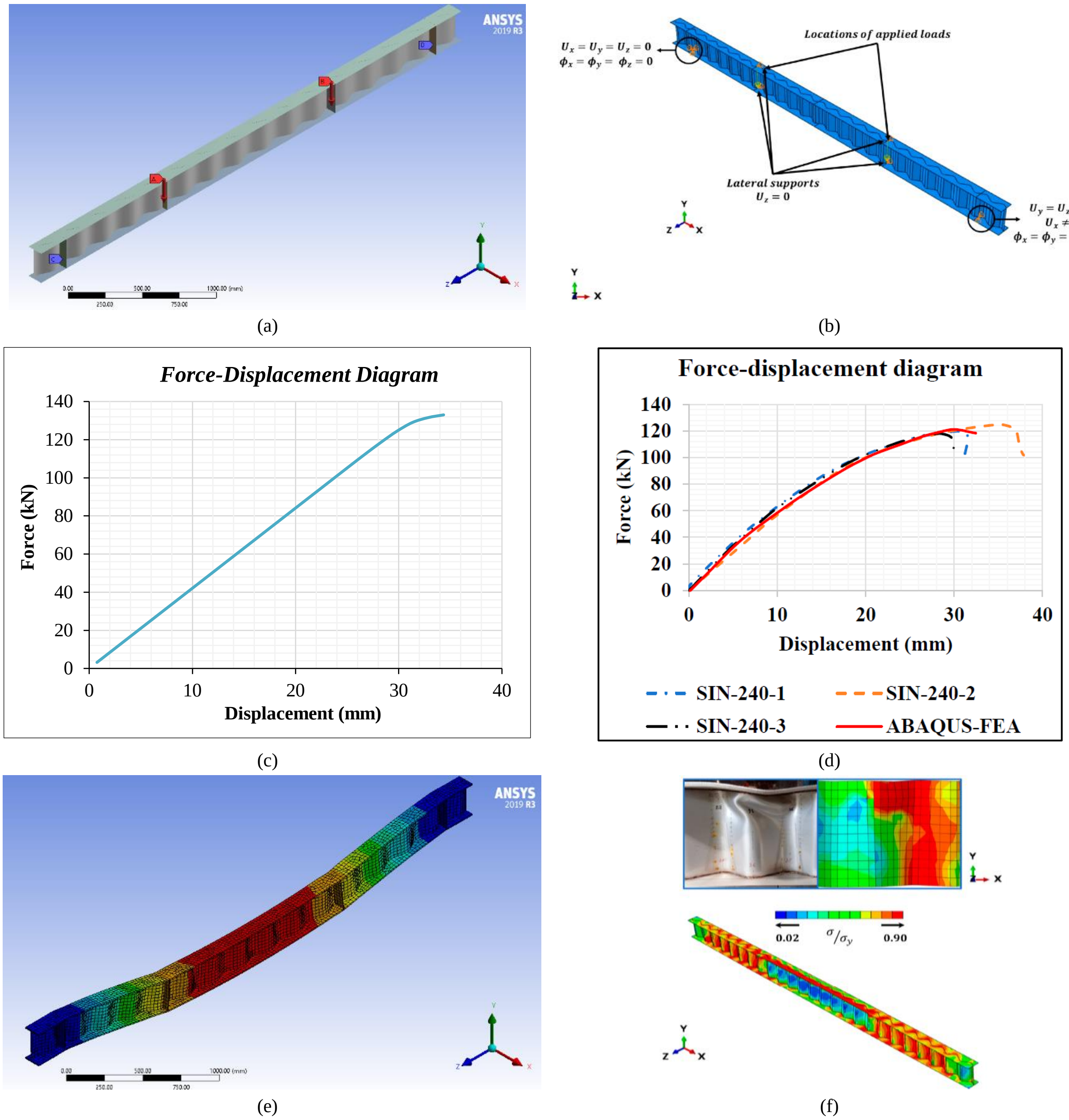

Figure 8. (a) ANSYS Finite Element Model, (b) Finite Element Vitrification Model [27], (c) Force-Displacement Diagram, (d) Force-Displacement Diagram for Vitrification Model [27], (e) Failure Mode shape and (f) Failure Mode shape for Vitrification Model [27].

4. Results and Discussion

The effect of various parameters of the steel beam with sinusoidal profiled web on the deflection, failure load and failure mode were examined.

4.1. Effect of Variation of Amplitude/Period Ratio

In the first stage, all samples with the same span length and sine waves with varying amplitudes (by maintaining the period of the sinusoidal web profile of 250 mm and changing the amplitude/period ratio, A/P of 0.5, 0.4, 0.3, 0.2, 0.1, 0.06, 0.04, and 0) as described in Table 1 and Figure 9. For all of these cases the equivalent Von Mises stress, shear stress, directional displacements, and failure loads are calculated. The variation of the failure load for the various values of A/P is shown in Figure 10. From this figure it can be noticed that the optimum A/P ratio is 0.1 which results in maximum Von-Mises failure load.

Table 1. Variations of Amplitude/Period ratio A/P with period of 250 mm

Sample No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Amplitude /Period ratio A/P	0.5	0.4	0.3	0.2	0.1	0.06	0.04	0
Amplitude (mm)	125	100	75	50	25	15	10	0

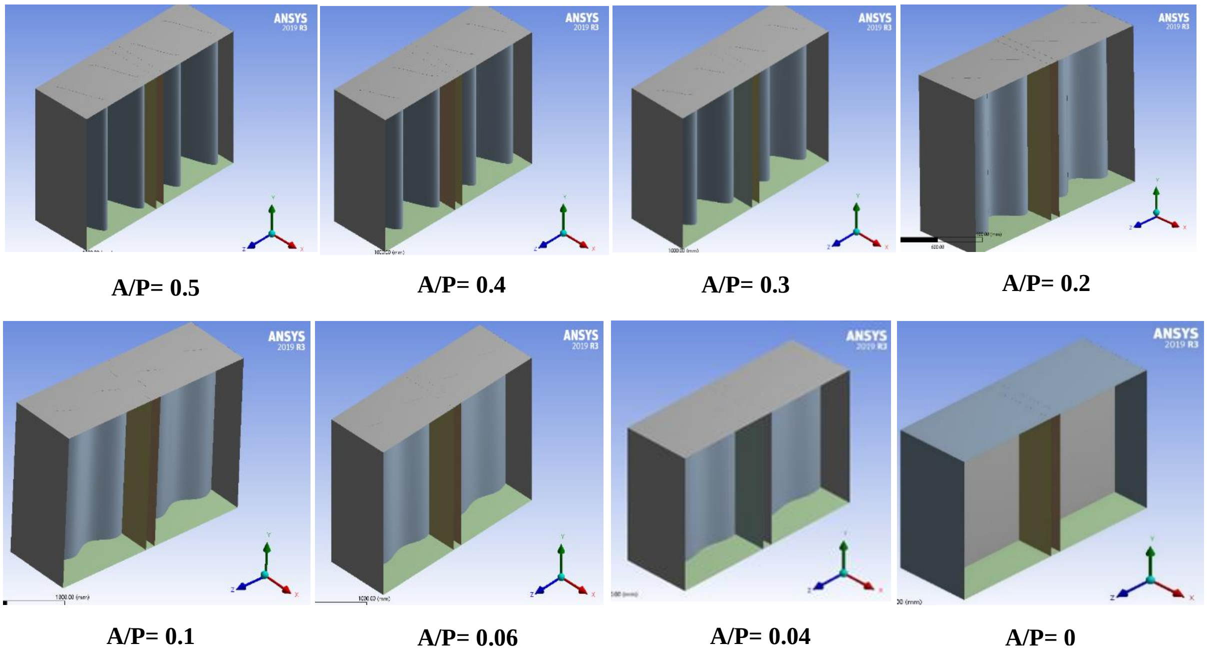

Figure 9. Cases Considered for Effect of Amplitude/ Period Ratio

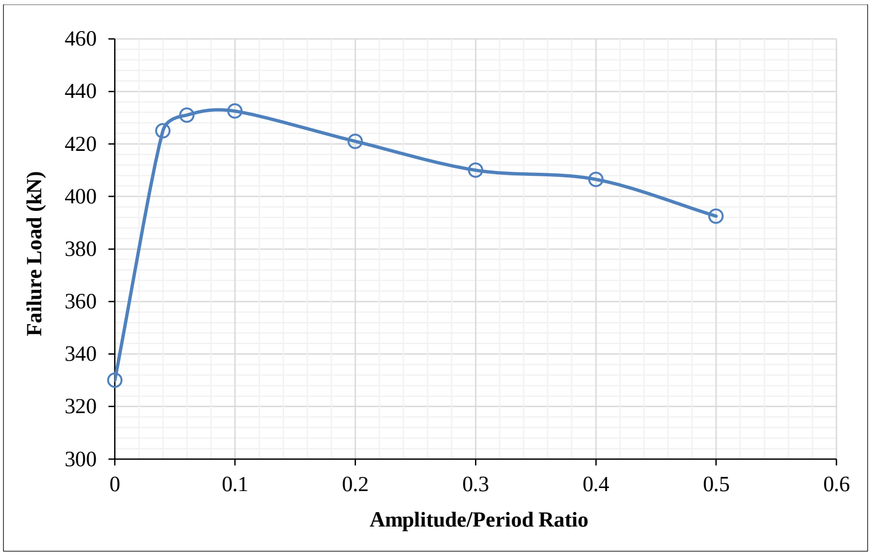

Figure 10. Variations of Failure Load with Amplitude/Period Ratio

From Figure 10, it is evident that when the A/P ratio rises, the loads increase significantly before somewhat decreasing again. This is effective in terms of the amount of raw materials used and the bending technique. The ideal A/P ratio must be carefully selected to create a more cost-effective web with a greater load-bearing capability. It is worthy to notice the significant effect of the smaller sinusoidal A/P of 0.04 on the load capacity compared with the straight web; the increase in load capacity reached 28.7%. However, the biggest increase in load capacity reached 31% at A/P of 0.1.

For A/P > 0.1, it's obvious that the load capacity tends to decrease, but it is kept above the straight web capacity due to sufficient stiffness and stability. From Figure 11, it is clear to attention that the sinusoidal web keeps carrying more shear stresses and fewer bending stresses with the increasing of the A/P ratio. The increasing of shear stresses after A/P=0.2 tends to be a slight increase and going to be straight and satiable forward. So, no need to go up to A/P=0.2 to save material and prevent the local shear buckling.

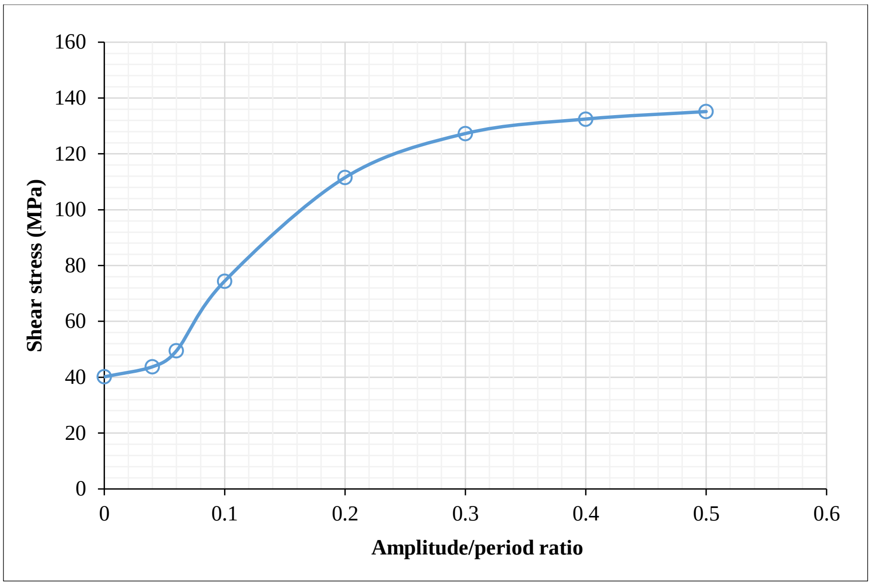

Figure 11. Variations of Shear Stress with Amplitude/Period Ratio

Mode shapes in Figure 12 demonstrate that a local shear buckling occurs in a straight web (A/P=0) and vanishes in a sinusoidal web with varying A/P ratios. The majority of web materials are utilized to withstand applied loads with enough structural stability and without buckling when the A/P ratio is between 0.1 and 0.2. As can be seen from the above, the ideal A/P ratio is between 0.1 and 0.2, which leads to the highest Von Mises stresses, the least amount of buckling, and increased stability.

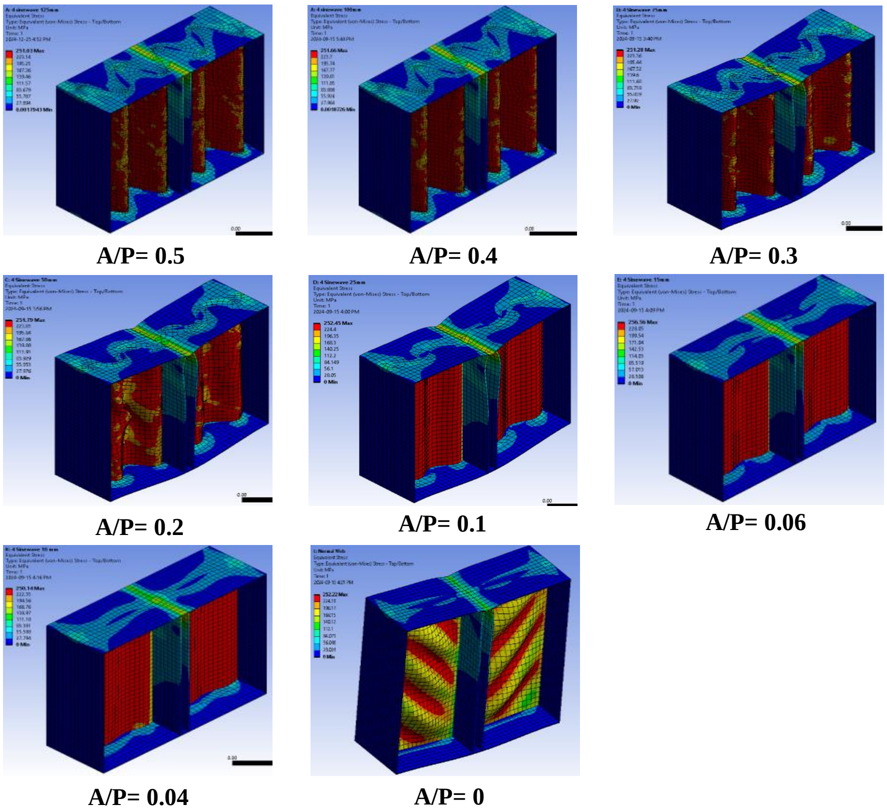

Figure 12. Mode Shapes of Cases Considered for Effect of Amplitude/ Period Ratio

In comparison to a straight web, which exhibits weak tolerance to shear stresses, the emergence of numerous localized buckling and higher displacements that cause the structural member to fail to bear more of the applied loads weakens its efficiency and precludes its use in members exposed to high shear loads. The results generally showed that the use of beams with a sinusoidal web is more efficient, economical, and load-bearing. This is because there is no buckling of any kind, and the beams have a high tolerance to shear stresses resulting from the applied loads.

4.2. Effect of Period/Span Ratio

In the second stage, the optimum amplitude/period ratio (A/P) of 0.1 as obtained in the previous section was adopted with varying the period with respect to span length, which was maintained at 1000 mm. Seven values of the period/span (P/L) ratios of 1.0, 0.5, 0.333, 0.25, 0.20, and 0.167 were examined to calculate the equivalent Von Mises stress, shear stress, directional displacements, and failure loads as shown graphically in Figure 13. The period/span ratio yields the maximum failure load, keeping those shear stresses and directional displacements within the allowable limits, and is considered to be the optimum one. The relation between the period/span ratio and the failure load is shown in Figure 14. From this figure, it could be noted that the maximum failure load was obtained for a period length of 0.5.

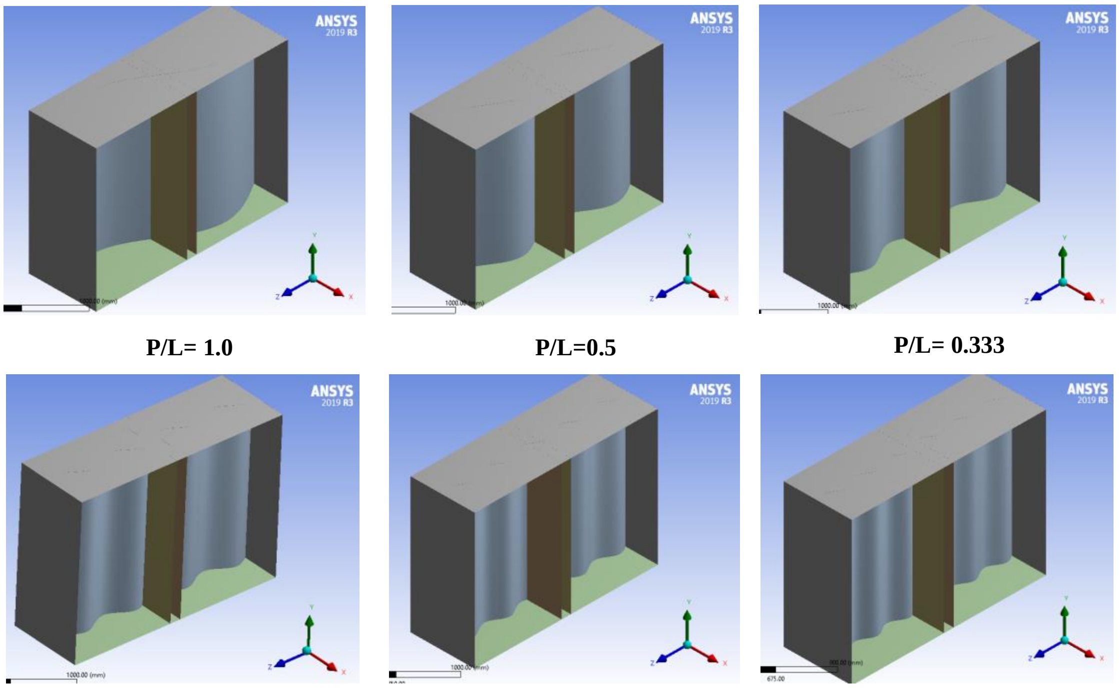

Figure 13. Variations of Period with Optimum Period/Amplitude ratio P/A

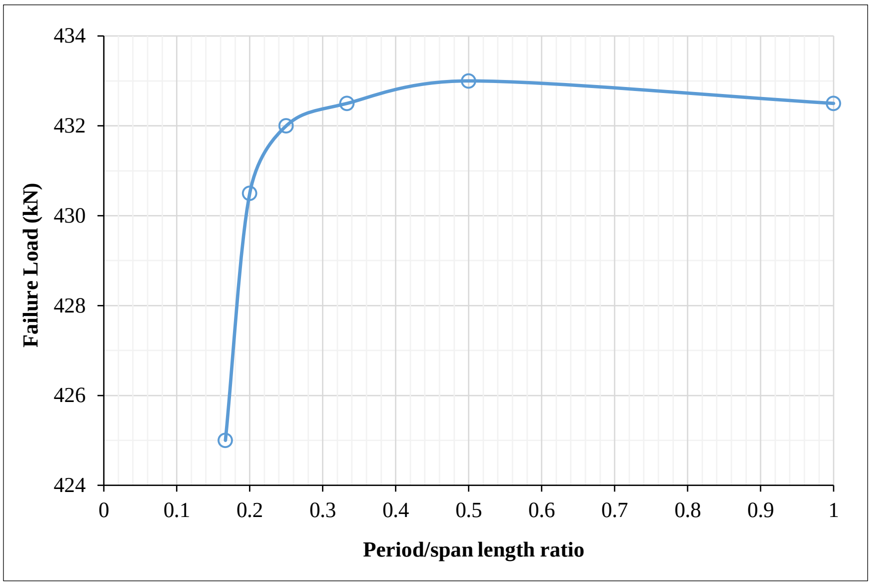

Figure 14. Variation of Failure Load with Period/span length ratio

Practically speaking, the results in Figures 14 and 15 are advantageous since they indicate that a smooth sinusoidal wave of the web can be used to achieve a better load capacity. Additionally, it indicates how much the web's minor curvature increases load capacity as compared to a flat web. Because of the maximum failure stress and minimal curvature, the period/Span length ratio of 0.5 appears to be the ideal ratio.

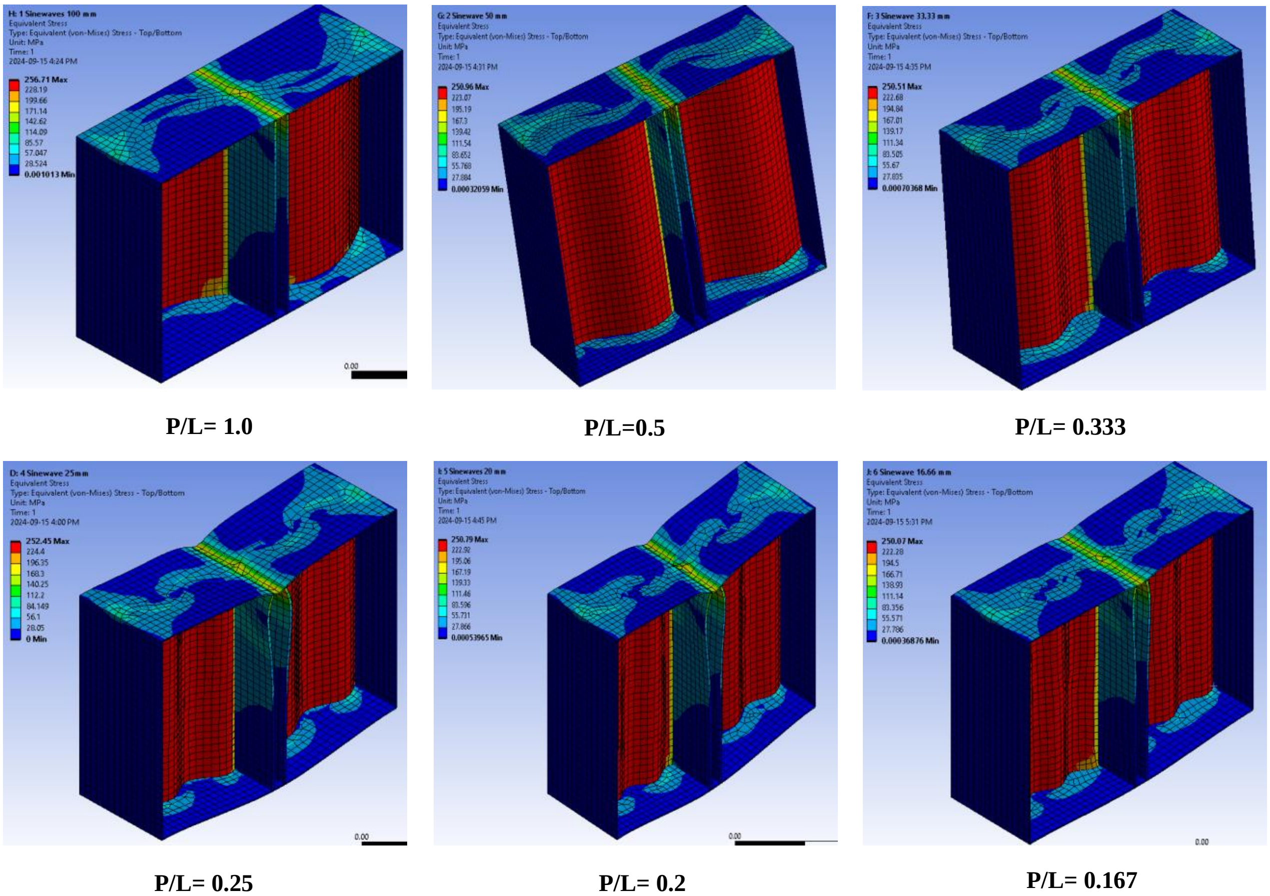

Figure 15. Mode Shapes of Variations of Period with Optimum Period/Amplitude Ratio P/A

Figure 16 show the expected increasing in load capacity with the increase of plate thickness. It also shows the same trend of effect of A/P on the load capacity of the beam for different plate thickness.

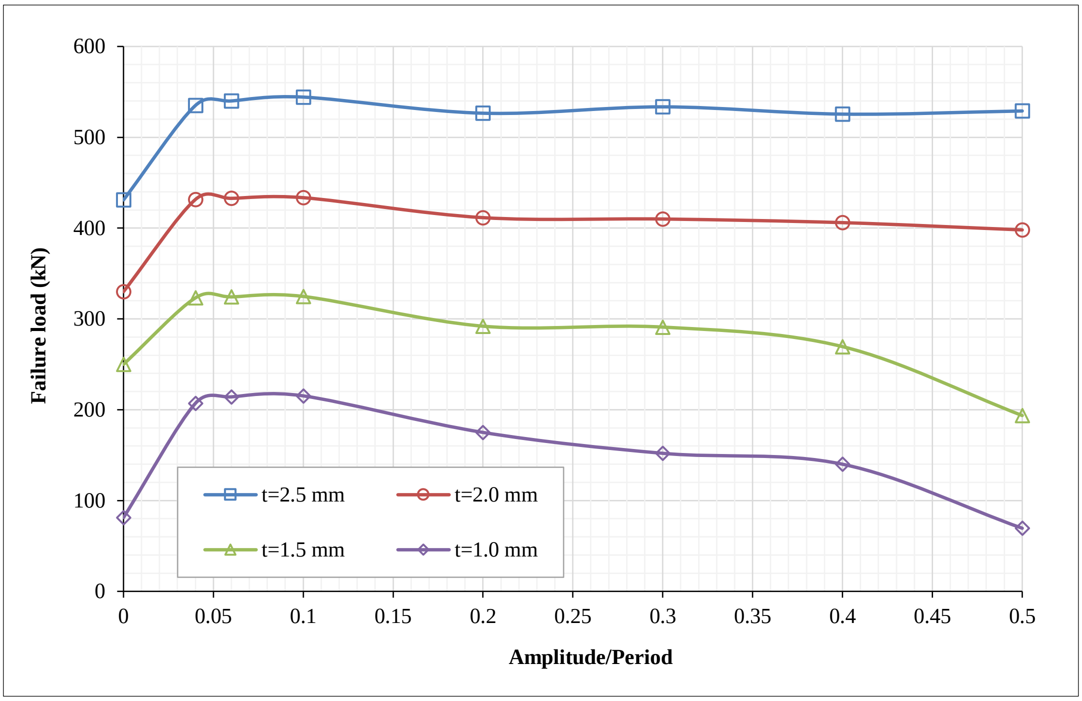

Figure 16. Variation of Load capacity with plate thickness and A/P

5. Conclusions

- According to the literature mentioned above, not much research has been done on how changing the sinusoidal web's period length and amplitude of an I-steel beam impacts applied loads and failure mode geometries.
- In this study, in order to simulate practice behavior, I-steel with a sinusoidal web with varying amplitude/period and period/span ratios was modeled using nonlinear finite element analysis. A unique FEA result for an I-steel beam with a sinusoidal web based on varying the period length and amplitude is presented in this paper. By analyzing the failure capacity loads and deformed shapes, the goal of this work was to determine the optimum amplitude/period and period/span ratios.
- For verification purposes, the validity of the current study model was examined in terms of the accuracy of the outcomes by modeling, analyzing, and comparing the results of earlier experiments. In terms of accuracy with the findings of the earlier research, the analyses produced positive results.
- The study shows that there is a significant improvement in the load-carrying capacity of a steel beam with a sinusoidal web over a steel beam with a straight web.
- Regarding the Amplitude/Period ratio, this improvement was achieved in the current parametric study on a beam with a 1000 mm span by reaching optimum values of Amplitude/Period to be between 0.1-0.2 due to an increase in failure load capacity and minimized deflection and curvature.
- Regarding the Period/Span ratio, this improvement was achieved in the current parametric study on a beam with a 1000 mm span by reaching optimum values of Amplitude/Period to be only 0.5 due to an increase in failure load capacity and minimizing the deflection and curvature.

5.1. Future Works

- It can be verified the results sensitive due to the variations in material properties, such as yield strength or modulus of elasticity.
- It is possible to confirm that the results are sensitive to changes in the beam's span length.
- The results' sensitivity to modifications in type of boundary conditions can be verified.
- To assess performance variations, the present findings could be contrasted with those of trapezoidal or corrugated-web beams.

6. Declarations

6.1. Author Contributions

Conceptualization, J.A.M. and M.A.K.; methodology, A.A.A.; software, J.A.M.; validation, J.A.M., M.A.K., and F.H.M.; formal analysis, M.A.K.; investigation, J.A.M.; resources, J.A.M.; data curation, A.A.A.M.; writing—original draft preparation, J.A.M. and M.A.K.; writing—review and editing, J.A.M. and M.A.K.; visualization, F.H.M.; supervision, A.A.A.; project administration, A.A.A.M.; funding acquisition, J.A.M., M.A.K., and A.A.A.M. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

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6.4. Conflicts of Interest

The authors declare no conflict of interest.

7. References

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