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Self-Weight Minimization of 3D-Printed Corrugated Web Beams Using Finite Element Analysis

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Abstract

Additive manufacturing, commonly known as 3-D Printing, is a relatively new manufacturing method. Although it is now widely used in the industrial field, its use in structural field is still very limited. A few works were made to explore the potentiality of using additive manufacturing in structural engineering. This paper is devoted to exploring the benefits of additive manufacturing in the field of structural engineering and more specifically, steel structures. The objective is to explore the possibility of modifying the shape of structural systems to decrease their weights, without effecting their performance and load carrying capacity. This will show how advantageous can the use of additive manufacturing in the field of structural engineering be, since complexity of fabrication is not a problem and does not add any cost, while the overall cost of the beam will be reduced by reducing its weight. Initially unmodified-shape model of a corrugated web beam was analyzed using Finite Element Analysis and then the shape of the cross section was modified following the stress contours. Finite Element Analysis was conducted on the modified-shape model and the results were compared with those of the original model. It was found that the modified model could withstand the same loadings as the original one with 19.26% reduction in weight.

Keywords: *Metal additive manufacturing, Finite element analysis, Corrugated web beam.*

I. Introduction

The biggest challenge a structural engineer faces is perhaps attempting to balance the safety and the cost, being limited to what's available on the market. This forces the designers to choose designs that are not optimal in cost, since safety is a major requirement. For an example, when designing an I-beam, the designer might find himself selecting a section with a load carrying capacity that suits the required loading, but has the problem of a slender web that causes a failure by local buckling. This problem can be solved by using a section with a thicker web.

However, when trying the find a section with a thicker web from what's available, the designer might find himself with a section of a higher load carrying capacity that's unnecessarily heavier than needed. This problem can be solved if the designer could have special customized sections without limitations, and without adding too much on the costs. Such a solution can be achieved using additive manufacturing technology. In their paper, Eleonora and Salmi (2012) reviewed the economics of creating end-usable metal parts

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using AM techniques compared to traditional ones. It was found that AM reduces the time and cost of the design phase.

A special type of steel girders is the corrugated web beams, an I-beam with a web that is corrugated along its length. This type of beams has proven to be advantageous in terms of cost, stability and load carrying capacity. In a study by Prathebha and Jane Helena H (2018) it was shown that a reduction in cost of 10-30% in comparison with the conventional fabricated sections and more than 30% compared with standard hot rolled sections could be achieved using corrugated web beams without affecting the carrying capacity. However, this type of beams has its limitations since the manufacturing process it requires can be difficult and requires special equipment and experienced labor especially for the assembly and welding processes. Such a problem can be eliminated using the additive manufacturing technology. Also, the welding process can affect the performance of the beam as found in the study by Raiza Ashrawi et al. (2016). In that study, finite element analysis models were created for vertically corrugated web beams, the results were compared to similar models tested experimentally in another study (Khalid et al., 2004). An error of 17.21% was found between the experimental and the finite element analysis results, it was suggested that the error is due to the welding process of the web and the extreme heat produced in the welding process that can change the mechanical properties of the steel. As a result, the experimental beam had a significantly less load carrying capacity than the finite element model.

The full potential of additive manufacturing for corrugated web beams that we wish to explore does not stop at eliminating these problems. Since limitations on the design does not exist, we will try to reach an optimum design, suitable for a certain loading condition, with the minimum possible weight. Previous studies attempted to minimize the weight of beams without affecting their performance. Kumbhar and Jamadar (2015) attempted to optimize the size of openings in the web of castellated I-beams. Krishnarani and Mohanan (2016); Kiymaz et al. (2010); Kiymaz et al. (2007) explored the performance of castellated corrugated web beams. These studies showed great results, but geometrical limitations still exist, in addition to the fact that creating such openings in the web would increase the time and cost of manufacturing.

II. METHODOLOGY

A model of a corrugated web beam 5 m long, 200 mm deep, and 100 mm flange width was selected. Figure 1 shows a 3D model of that beam, as well as its details and dimensions. The 3D model created using 3Ds Max software was imported into the finite element analysis software ANSYS AIM 18.1. The analysis was conducted on the beam under the conditions of simply supported ends and two-point concentrated loading. Values of stress and vertical displacement was obtained from the analysis, and the displacement was plotted against the total load. After the analysis, the stress flow throughout the beam was investigated. According to the stress distribution, the web and flanges of the beam were resized at different locations assigning more thickness where the stress is high and less thickness where the stress is low, in order to obtain the minimum possible weight. The new models were then imported into ANSYS AIM 18.1 and the analysis was conducted again under the same conditions, and the vertical displacement was plotted against the total loading to be compared with the original plot, finally the weights of all models were calculated and compared with each other.

Non-linear analysis was used, the properties of the steel used are shown in the accompanying table. For the mesh, quadratic/triangular meshing method was used to capture the differences in geometry of curved and planer surfaces. Also, automatic meshing sizing was used to account for the different thicknesses of different sections

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especially with the parts of varying thicknesses along the length. Theoretical cylindrical steel part of a much stronger properties were used to simulate the supports and testing machine head as shown in Figure 2.

Property	Value	Unit
Young's Modulus	2E+5	MPa
Bulk Modulus	1.667E+5	MPa
Shear Modulus	76923	MPa
Poisson's Ratio	0.3	-
Yield Strength	250	MPa
Tangent Modulus	1450	MPa

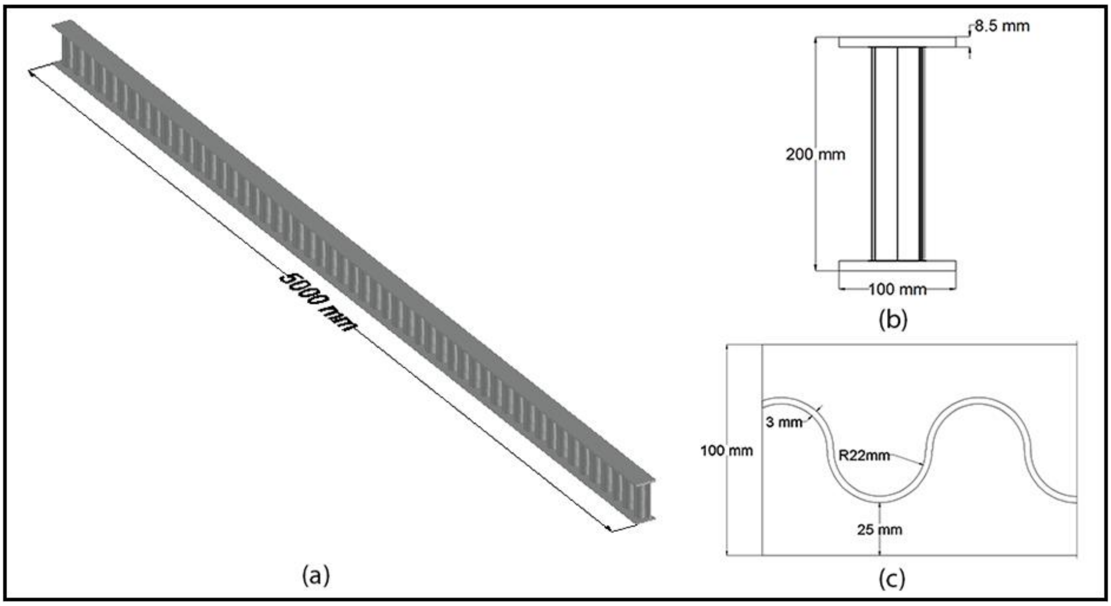

Fig 1: (a) 3D model of the corrugated web beam (b) the cross section of the corrugated web beam (c) the corrugated web.

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III. RESULTS AND DISCUSSION

For the analysis of the original beam, a vertical downward force was applied at the two cylinders of distances of 1953 mm from both ends of the beam, the force reactions of both supports as well as the maximum vertical displacement were obtained for the purpose of plotting the force against the displacement for the beam. Under these conditions a maximum stress occurred at the lower-flange mid-section area, showing that flexural behavior controls over the beam, the maximum force reaction on the end supports was 65.1 KN and the deformed shape indicates no loss of stability.

The deformed shape of the beam, as well as the mesh, are shown figure 2, and the force-deformation diagram is shown in figure 7. The stress flow throughout the beam shows gradually decreasing values on the flanges away from the points of loading, and gradually decreasing values on the corrugated web away from the points of supports at the ends of the beam. Three attempts to reduce the weight without affecting the performance of the beam were carried out in certain locations depending on the stress flow, by reducing the thickness of the web, reducing the depth of the beam, and reducing the width of the flanges.

Reducing the thickness of the corrugated web

Since the web plays little to no role in the moment carrying capacity of the beam and is mainly important for shear, a thicker web at the ends of the beam is more important than at the center due to the moment and shear distribution of the simply supported beams. The design was modified so that the thickness of the web is variable along the length of the beam following the profile shown in figure 3.

Finite element analysis was performed on the modified model under the same conditions, and a force-deformation diagram was plotted. The force deformation diagram of the modified design (M1) is shown in figure 8. As evident from the analysis, the modified model (M1) performed very well and close to the original beam with very slight differences.

Reducing the depth of the beam

Since the moment decreases the further we move away from the points of loading until it reaches zero at the ends of simply supported beams, it isn't necessary to keep the depth the same along the entire length, and this concept is compatible with the stress flow in the flanges which are mostly responsible for the flexural capacity of the beam. A modified design (M2) was created with the depth of the beam being variable along its length following the profile shown in figure 4.

Again, finite element analysis was performed on the modified model under the same conditions, and a force-deformation diagram was established. The force deformation diagram of the modified design (M2) is shown in figure 9. As evident from the analysis, the modified model (M2) also performed very well and close in terms of load carrying capacity and deformation to the original beam with very slight differences. Both modifications reduce the weight of the beam significantly without affecting its performance. The reduction of weights will be discussed later.

Reducing the width of the flanges

Another approach of taking advantage of the fact that the moment decreases near the ends is by gradually reducing the width of the flanges of the beam the further we move away from the points of loading. A modified design (M3) was created following that concept. However, since the stress flow shows some differences between the upper and the lower flanges, differences in the width profile was needed to be made. The width profiles of both the upper and lower flanges is shown in figure 5.

Once again, finite element analysis was performed on the modified model under the same conditions, and a force-deformation diagram was established.

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The force deformation diagram of the modified design (M3) is shown in figure 10. As evident from the analysis, the modified model (M3) performed very well and close to the original beam with very slight differences, also with a significant reduction in weight without affecting the performance of the beam. Figure 6 shows the 3D models of the original, and the modified models, and figure 11 shows the convergence diagram for each model.

IV. COMPARING THE RESULTS

The analysis showed very close results of the load carrying capacity and displacement of the original corrugated web beam, and the modified models as shown in figure 11. Using a steel density of 7850 kg/m3 it was possible to calculate the weight of each beam model and the reduction in weight of each modified model, compared with the original corrugated web beam model. It is evident that for the variation in shear, the reduction in the thickness of the web reduced the total weight of the beam significantly, while for the variation in moment, the reduction in the width of the flanges resulted in a much lower weight than the reduction in the depth did, which is the method used the most. Mixing the modifications of both model (M1) and model (M3) to capture the variation in both moment and shear would result in a weight reduction of 19.26% without affecting the capacity of the beam. It should be noted that the number of iterations needed for the convergence to an optimum solution varied between each model as evident from figure 12.

V. CONCLUSION

The main objective of this study was to explore the benefits of using additive manufacturing in creating structural systems by optimizing the design to have a reduced weight without affecting the performance and load carrying capacity of these systems, which would result in a reduction in the total cost of materials. The study focused on a special type of structural elements namely the corrugated web beam, since it has many advantages regarding stability, but also has the problem of costly and difficult method of fabrication. Modifying the shape of these girders to reduce their weight would increase these difficulties significantly. Using additive manufacturing would alleviate these problems. It would not be only possible to create such beams with ease, but it would also be possible to create any modifications in their shape without introducing any additional difficulties.

Analytical investigation using finite element analysis on corrugated web beams showed that it is possible to save up to 19.26% of material by varying the thickness or the width of the beam elements using additive manufacturing technique without affecting the performance of the beam.

For future studies, it is possible to study the effect of a varying the thickness of the flanges of the beam, or the possibility of removing parts of the web were shear stress is minimum. An experimental study will be conducted in the future to validate the theoretical results.

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Beam model	Weight (KG)	Reduction in weight
Original corrugated web beam	100.53	-
Modified beam (M1)	89.17	11.30%
Modified beam (M2)	97.28	3.23%
Modified beam (M3)	92.52	7.96%

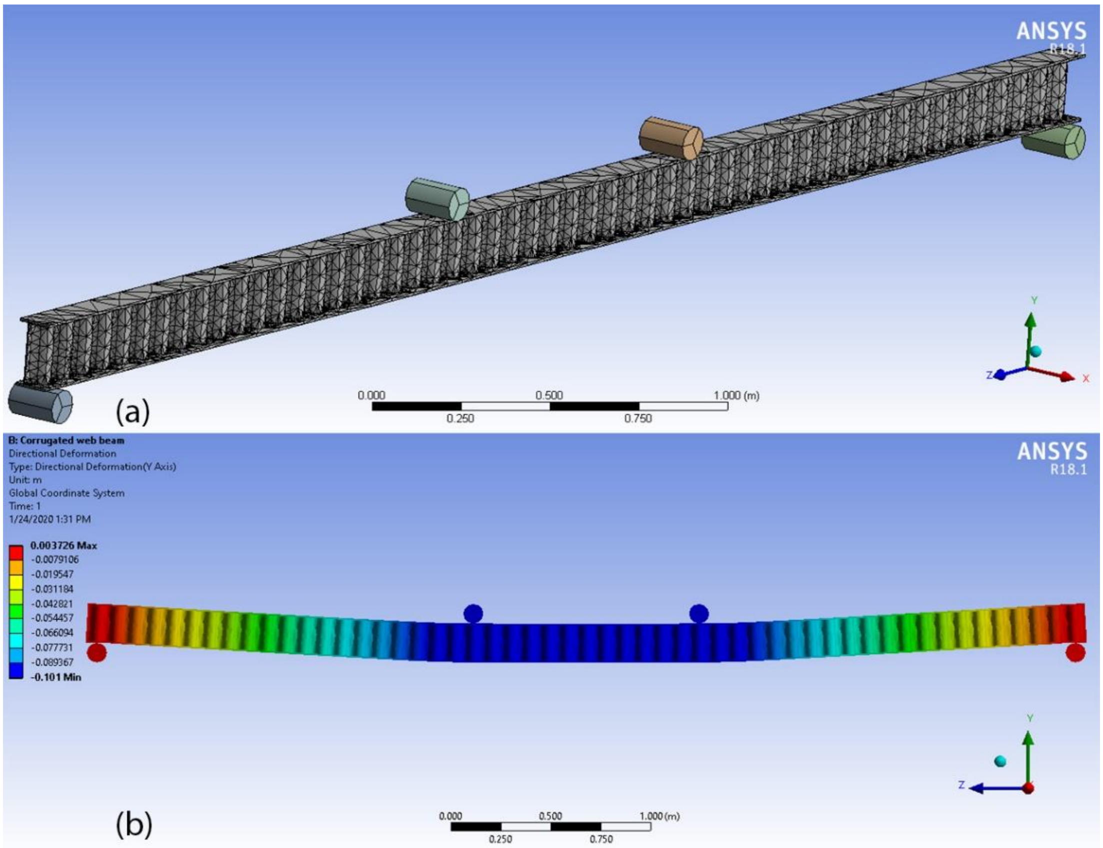

Fig 2: (a) the mesh used in the analysis (b) the deformed shape of the beam.

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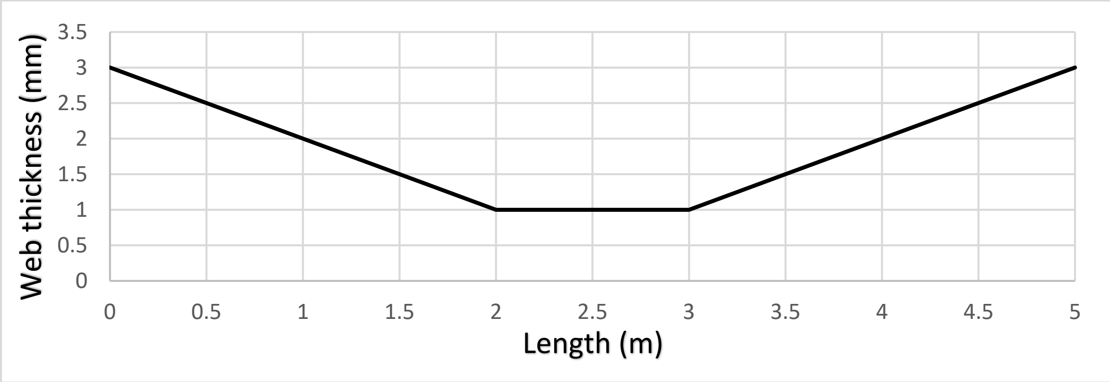

Fig 3: The thickness of web profile of the beam (M1) along its length .

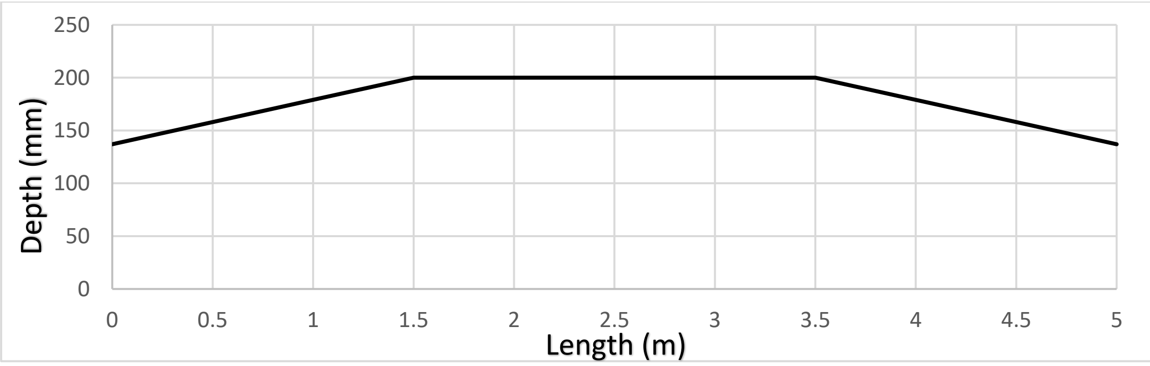

Fig 4: (a) The depth profile of the beam (M2) along its length.

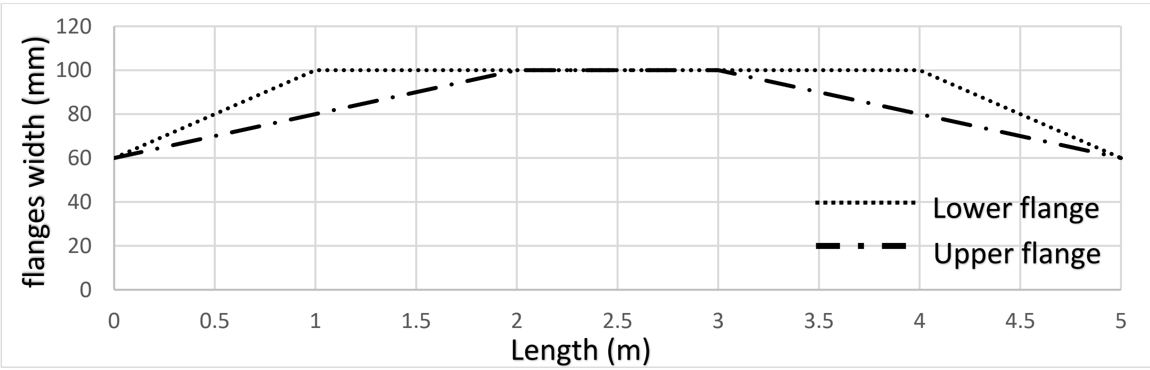

Fig 5: The width of the upper and lower flanges profiles of model (M3).

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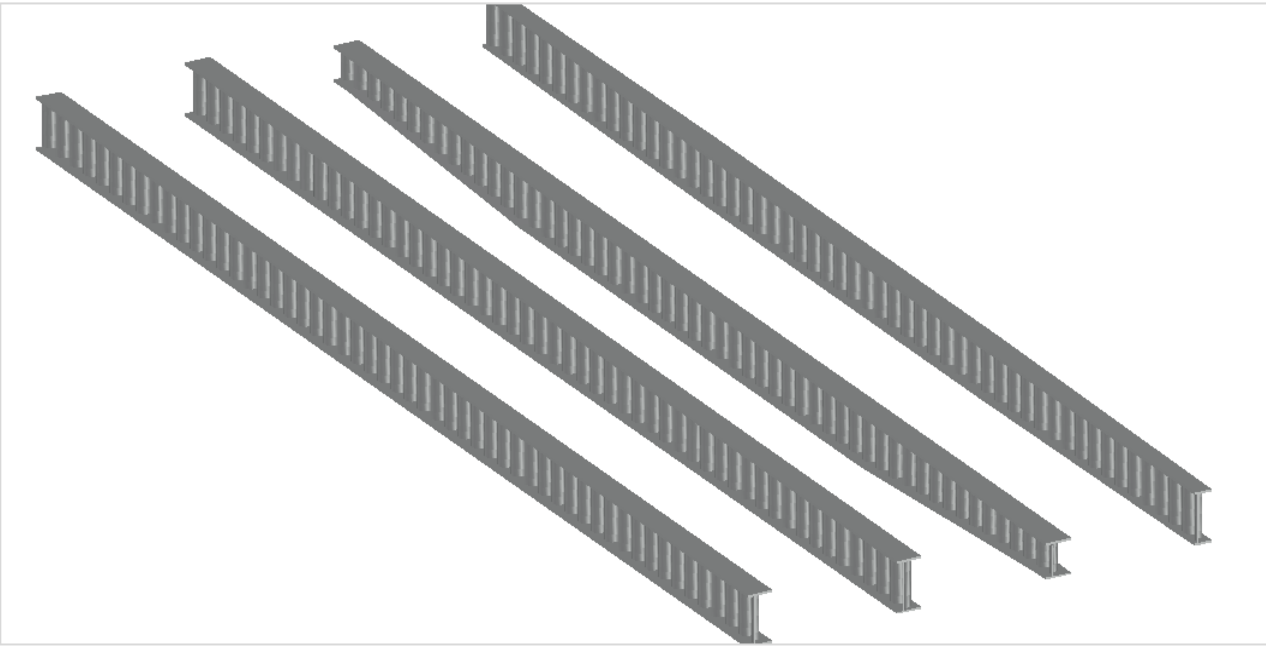

Fig 6: 3D models of the original and modified models.

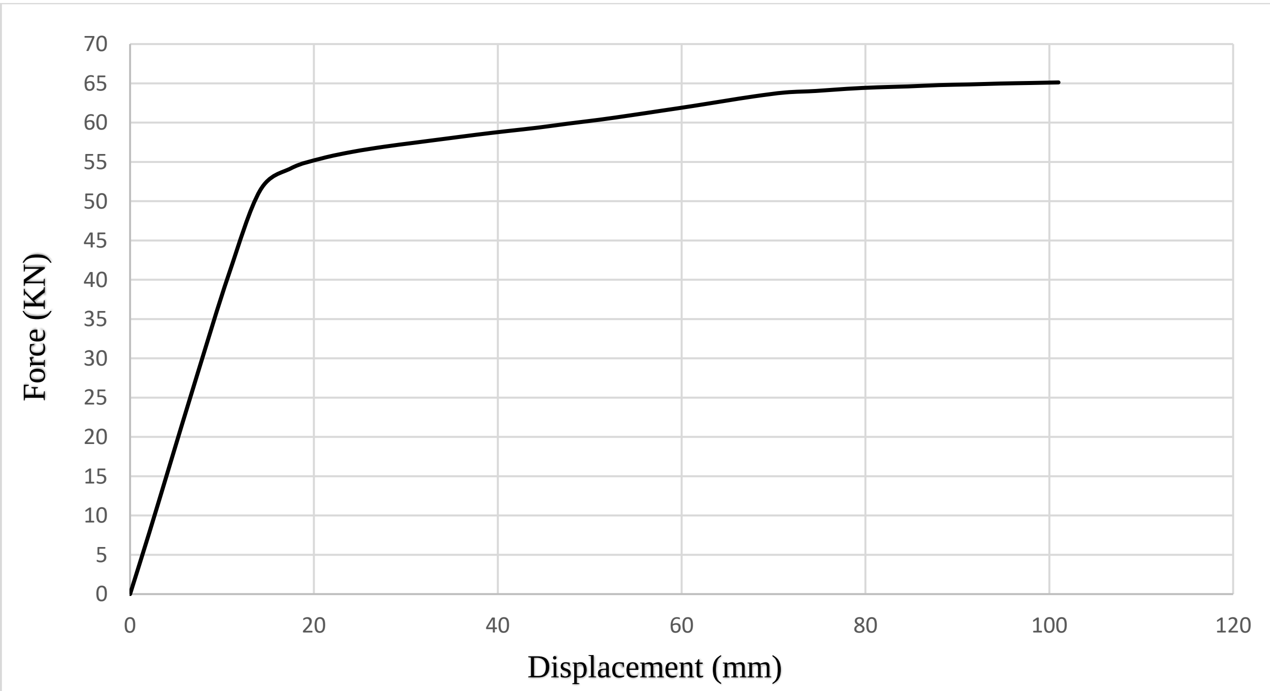

Fig 7: The Force-Displacement diagram of the original corrugated web beam.

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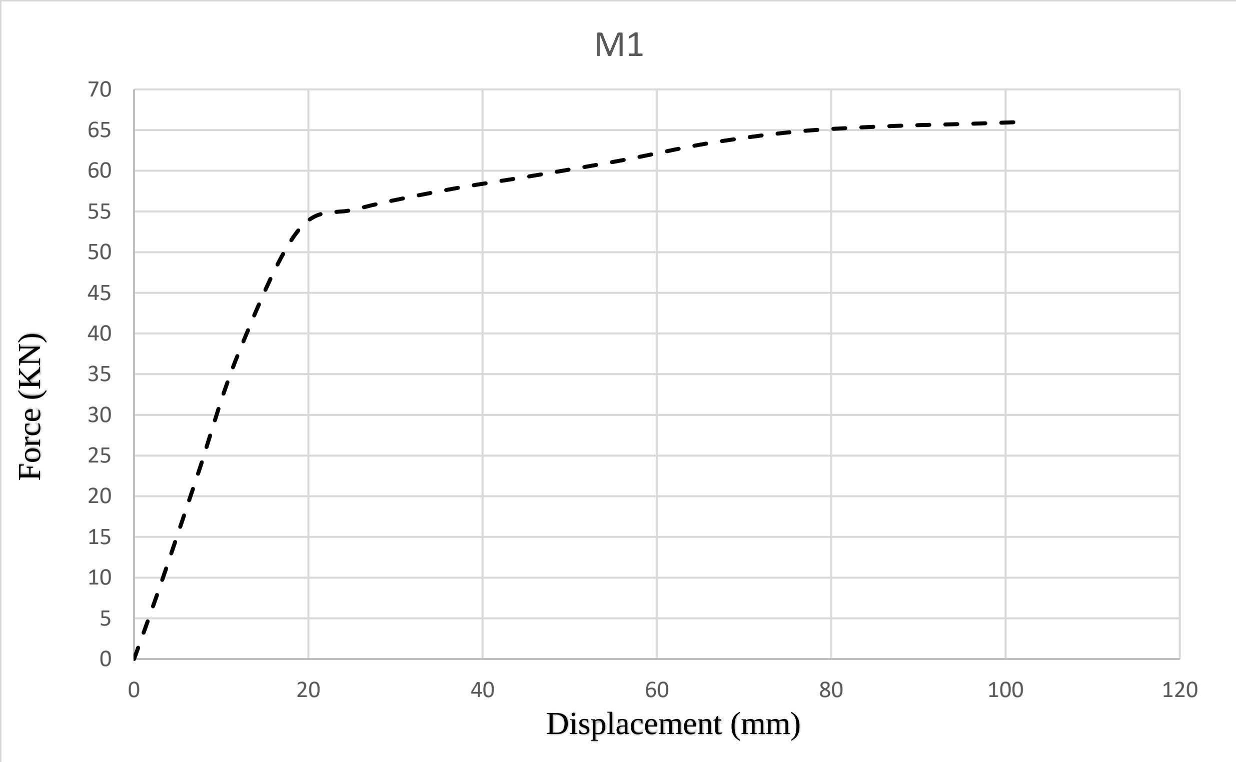

Fig 8: The Force-Displacement diagram of the M1 corrugated web beam.

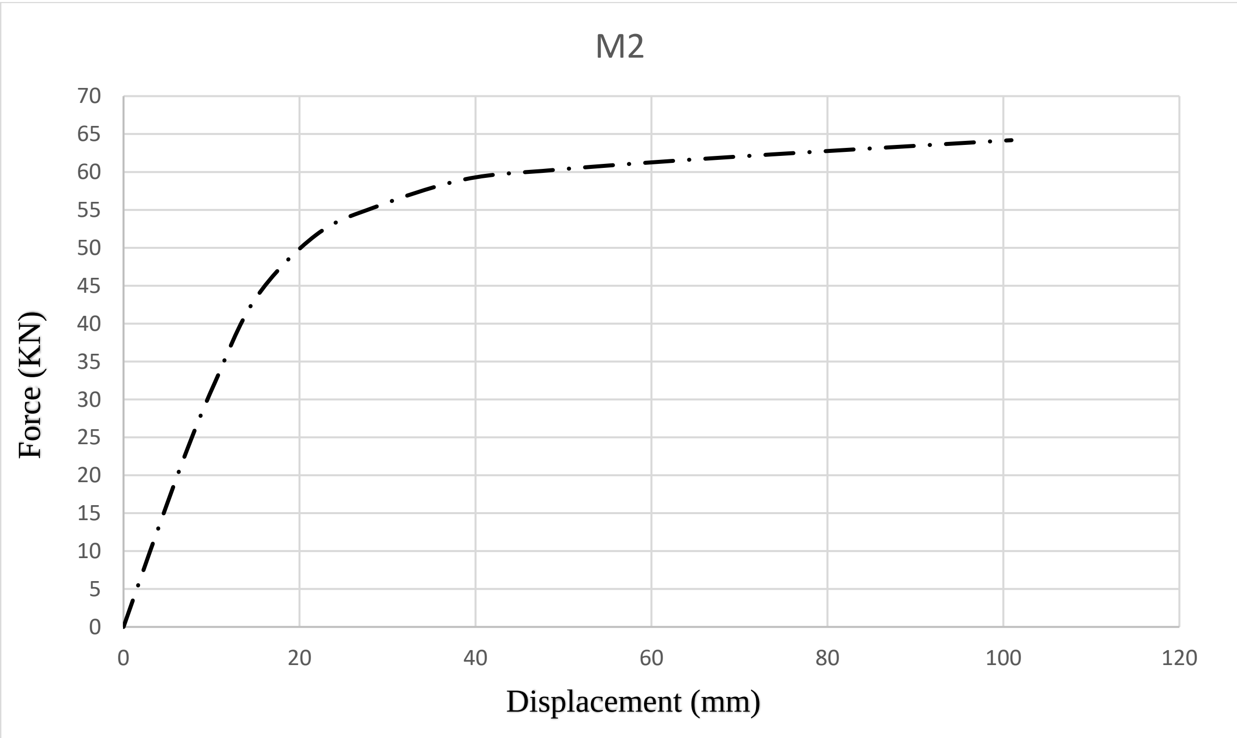

Fig 9: The Force-Displacement diagram of the M2 corrugated web beam.

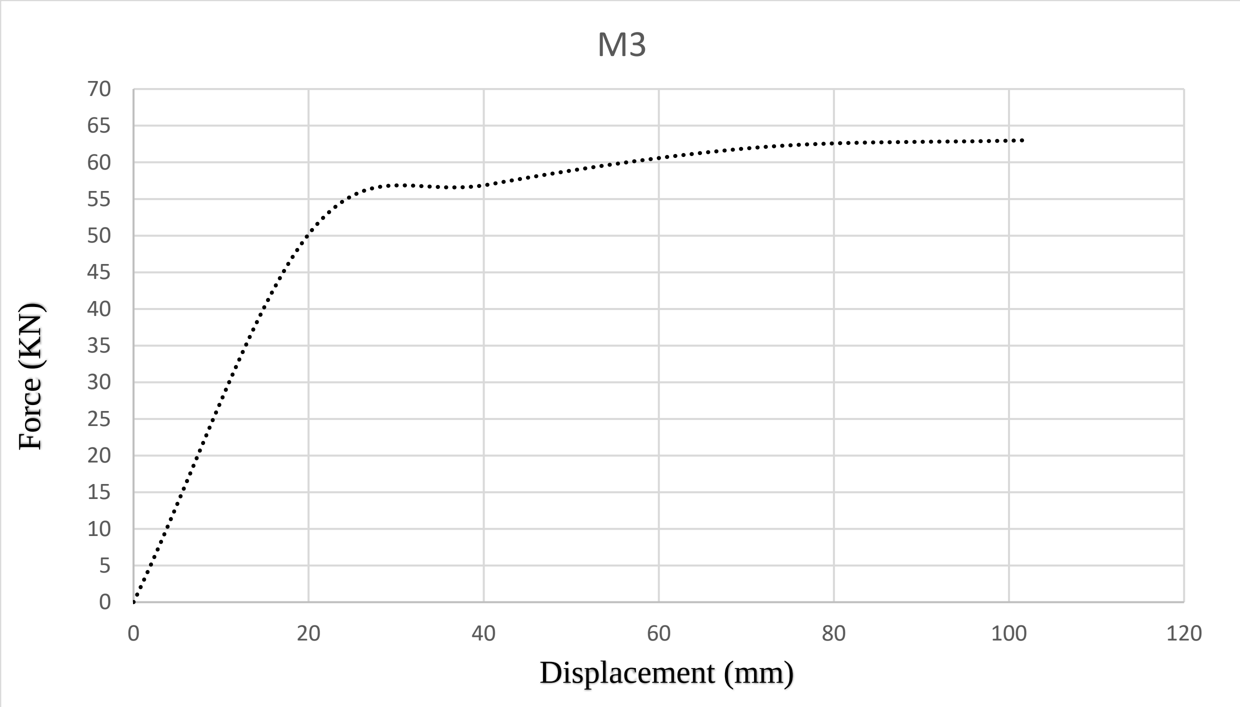

Fig 10: The Force-Displacement diagram of the M3 corrugated web beam.

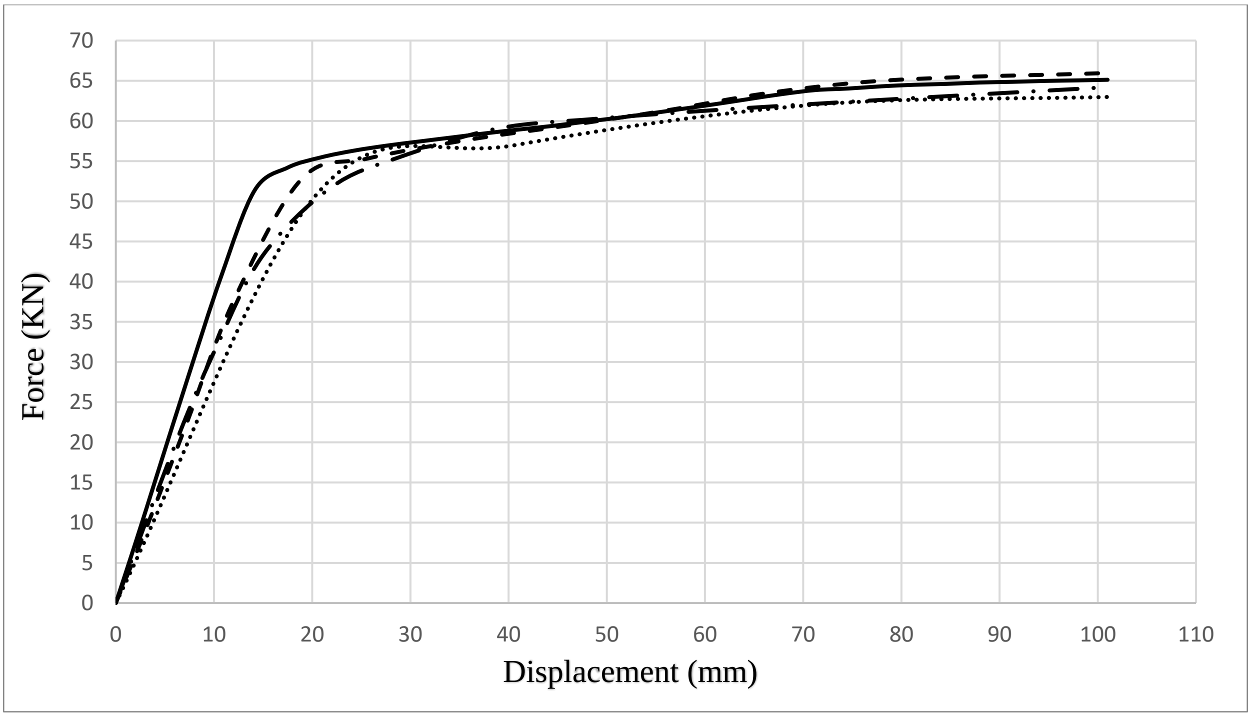

Fig 11: The Force-Displacement diagram of all model.

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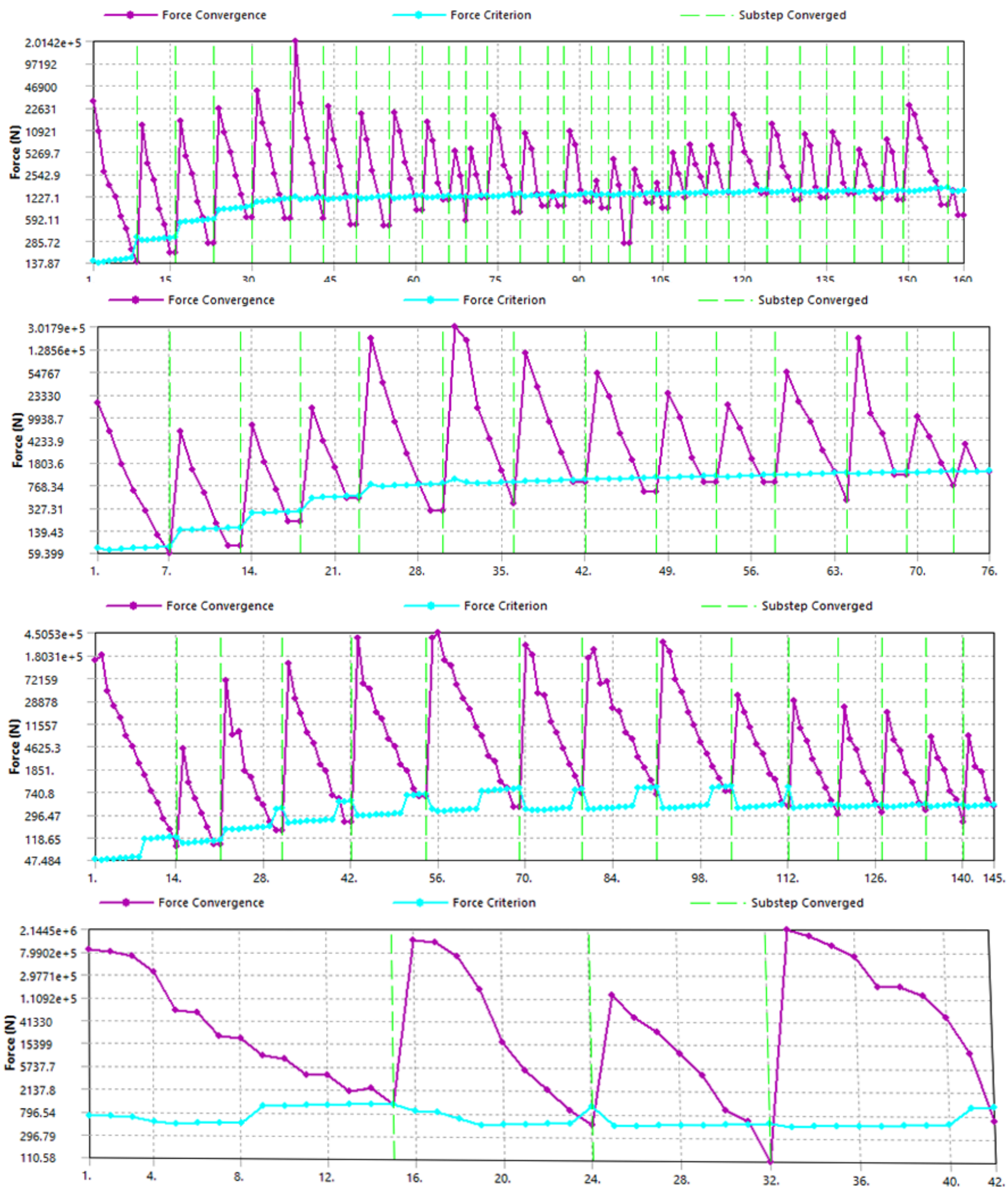

Fig 12: 3D models of the original and modified models.

VI. ACKNOWLEDGMENT

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