Applied Computer Science 2025, vol. 21, no. 2, pp. 28–36
https://doi.org/10.35784/acs_7308

Submitted: 2025-02-17 | Revised: 2025-03-20 | Accepted: 2025-04-28


*Keywords: eco-composite, FEM, buckling, numerical analysis, Euler's formula*

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# Buckling of a structure made of a new eco-composite material

**Abstract**

*This paper reports the experimental results of a study investigating a new eco-composite material made from 100% recycled material. Tensile and density tests were conducted. A numerical model of a one-sided fixed beam was designed by the finite element method and a buckling analysis of this structure was performed. Three different cross-sections and lengths of the beam were tested. The first fundamental buckling mode and the corresponding critical load value were determined. The obtained numerical results were verified by analytical method using Euler's formula, which showed high agreement between the results. The relative error was less than 4%. A higher level of agreement was obtained for longer beams than for shorter ones. The results obtained for the eco-composite were then compared with those reported for other materials with similar properties, namely LDPE, HDPE and PP. Compared to LDPE and HDPE, the eco-composite showed higher stiffness parameters and load resistance, which made the tested structure more rigid and therefore stable for a longer period of time. The analysis of beams with different cross-sections and lengths made it possible to determine the effect of these parameters on the critical load, providing valuable insights for designers. It was observed that a 100% increase in the initial rectangular cross-section of 800mm2 resulted in a 685% increase in the stiffness of the beam. A 100% increase in the initial beam length of 150mm resulted in a 75% decrease in the critical force. The results of this study have confirmed that the new eco-composite material can be effectively used in engineering structures.*

## 1. INTRODUCTION

For several decades, plastics have been widely used in many different industries and people interact with them on a daily basis. In 2021 alone, more than 390 million tons of plastics were produced worldwide. In the same year, approximately 4 million tons of new plastics will be introduced to the Polish market. With the increasing production of plastics, which could reach 1 billion tons per year by 2050, scientists and designers face serious challenges related to the problem of plastic waste and plastic recycling.

Previous research has shown that plastics can be recycled in a variety of ways. A review by Gada (2024) showed that it is feasible to use recycled plastics (PLA and ABS) in 3D printing, particularly in fused deposition modeling. Recycled PLA typically shows a decrease in mechanical properties, while recycled ABS tends to retain its properties better during recycling. Interestingly, 3D printed parts made from recycled materials often have smoother surface finishes.

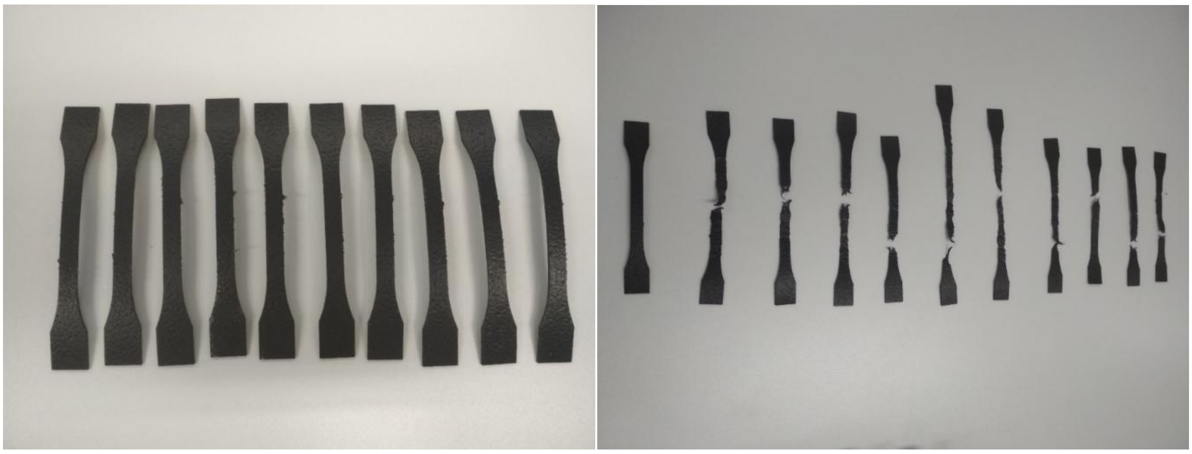
One way of using plastics in engineering is to blend them with wood and use this blend to make different types of boards. The properties of such blends have been studied by many researchers. Habibi et al. (2017) investigated the rheological behavior and mechanical properties of composites made of wood flour and a blend of two main components of plastic waste: low-density polyethylene (LDPE) and high-density polyethylene (HDPE). The effect of powdered fillers derived from renewable resources (such as wheat bran, pumpkin seed husks, and peanut shells) on the mechanical properties of LDPE was investigated by Sikora et al. (2019). The properties of recycled LDPE and HDPE were investigated by Murat et al. (2020). The study showed that the mechanical properties of the recycled HDPE and LDPE were closer to the virgin materials and that the materials have great potential for plastics recycling. Similar conclusions were reached by Müller et al. (2024) who investigated the recyclability of LDPE. They found that the properties of this material were not significantly degraded when the material was reprocessed. A large amount of plastic waste consists of bulky items that require size reduction during the recycling process (Pimentel Real, 2023). Głogowska and Rozpędowski (2016) investigated the effect of this process for LDPE. A detailed analysis of the effect of the size and shape of the openings in the sieves made in the shredder on selected parameters and properties of the obtained recyclate was performed. When studying the properties of new recyclate, a useful engineering tool is Digimat (E-Xstream engineering, 2016) for predicting the properties of material blends at a preliminary level, which helps to avoid the costs of producing real blends (Frącz et al., 2017).

A paper (Pfaendner, 2022) reviewed the last 30 years of research in the field of restabilization of recycled polymers, describing differences between virgin and recycled polymers. The author showed that similar to virgin plastics, polyolefin recyclates such as PP, HDPE and LLDPE/LDPE were the main stabilizer market. Therefore, a study was undertaken to test if these materials could be used in the production of structural components that are widely used in industry and everyday life, such as beams. Numerical models of a cantilever beam were designed in the Abaqus environment, and the structure was subjected to compressive loads. The first global buckling mode of the structure and the buckling-inducing critical force were examined. The tests were conducted on a new eco-composite made of 100% recyclate. The results were then compared with those reported for other materials, i.e. LDPE, HDPE and PP.

## 2. MATERIAL AND SAMPLE

The study involved the determination of material constants of a new material called eco-composite "Ekoforme". It was developed by the Ekoforme company, which produces structural components from this material for both the Polish and European markets. The material is a blend of polyolefins, i.e. LDPE, HDPE and PP, which are 100% recycled materials.

In the first stage of the study, tensile tests were performed on the eco-composite. Test specimens were prepared (Fig. 1a) by cutting them from an extruded homogeneous sheet of this material (Sawa et al., 2021). The dimensions of the specimens strictly followed the requirements of the ISO 527-1 standard Plastics - Determination of tensile properties (International Organization for Standardization, 2012) for tensile testing of plastic materials. The samples after destruction are shown in Figure 1b.



**a)** **b)**

**Fig. 1. Test sample: a) before destruction; b) after destruction**

The tests were performed on a ZwickRoell AllroundLine Z010 universal testing machine equipped with load cells with a maximum range of 10 kN, 500 N and 10 N, meeting the requirements of Class 1 according to EN ISO 7500-1 (Głogowska et al., 2022). The strain and width changes of the specimens were measured using a non-contact video extensometer of accuracy class 1 (according to EN ISO 9513), with a linear resolution of 1 μm for a field of view of 200 mm. The scanning speed was 5 mm/min. Specimens were clamped in mechanical self-clamping jaws and measurements were performed under laboratory conditions (23 ± 2°C, 50 ± 5% RH). The entire test process was monitored using testXpert III software. After testing 10 specimens, the average Young's modulus of the material was calculated to be 493MPa. The tensile strength of the material was determined to be 13.5 MPa. The stress-strain curves from the tests are shown in Figure 2.

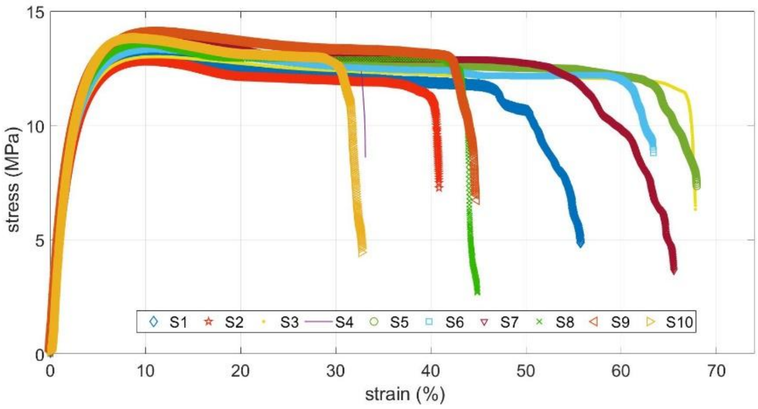



**Fig. 2. Tensile stress curves obtained from experimental studies**

The standard density ρ of the samples was then determined according to ISO 1183-1 A (International Organization for Standardization, 2019). This was done using the immersion method with water as the immersion medium. The density of the eco-composite was found to be 969 kg/m3.

## 3. NUMERICAL MODEL

As part of the study, numerical models of beams with different cross-sections and lengths were created for the purpose of buckling analysis. Each model of the analyzed structure was designed using S8R shell elements. Each beam was fixed at one end while the other end was free and subjected to a compressive load. An example of such a numerical model is shown in Figure 3.

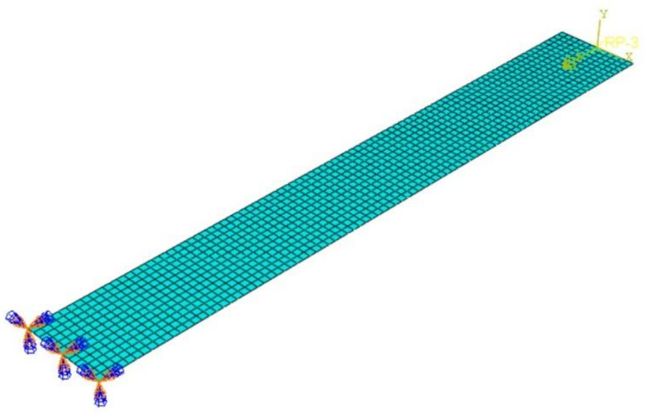


**Fig. 3. Numerical model of a beam**

The buckling analysis allowed to determine the critical load for each variant. The critical load is a very important parameter, because if it is exceeded, the structure will buckle, i.e., lose its stability (Różyło & Wrzesińska, 2016). Detailed tests were performed for three different cross-sections (mm): 40x20; 40x40; 40x60, and for three different lengths (mm): 150, 300, 450. The tested beam geometry variants are listed in Table 2. The numerical analysis was performed in the Abaqus environment (Abaqus HTML documentation, n.d.) using the finite element method.

**Tab. 1. Tested variants of beam geometry**

| Cross section | | Length | |
|---|---|---|---|
| Denotation | Dimensions [mm] | Denotation | Dimension [mm] |
| A1 | 40x20 | L150 | 150 |
| A2 | 40x40 | L300 | 300 |
| A3 | 40x60 | L450 | 450 |

The static test results obtained for the recycled eco-composite were then compared with the material data reported in the literature (Table 2) for other materials (i.e. PE, PP and LDPE). The Young's modulus, Poisson's ratio and strength shown in Table 2 were obtained from tensile tests.

**Tab. 2. Comparison of the properties of tested composite materials**

| | Eco-composite | PE100 (Ying et al.,2020) | PP (Drai et al., 2024) | LDPE (Bendarma et al., 2024) |
|---|---|---|---|---|
| $E$ [MPa] | 493±15 | 434 | 1100 | 250 |
| $\sigma$ [MPa] | 13.5±0.5 | 27.5 | 40 | 14 |
| $\rho$[kg/m^3] | 969±4 | 950 | 900 | 930 |
| $\nu$ [-] | 0.32±0.04 | 0.45 | 0.4 | 0.36 |

## 4. RESULTS

The static analysis made it possible to determine bifurcation loads reflecting the first mode of buckling (Fig. 4) for all analysed variants of beam geometry.

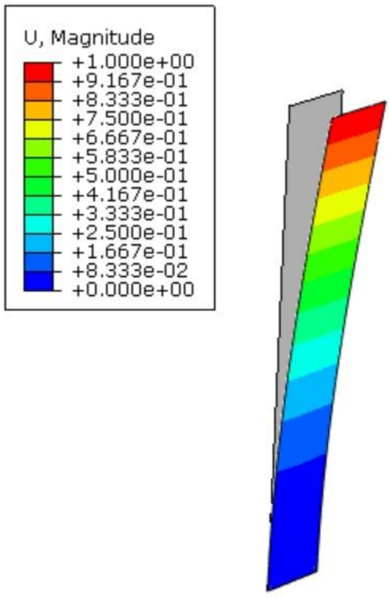



**Fig. 4. First buckling mode for A3 L450**

The Euler formula (Teter & Kolakowski, 2023; 2024) was used to verify the numerical results from Abaqus. The formula allows to determine the eigenload corresponding to the global buckling mode of an isotropic column under different boundary conditions (see Eq.1).

$$F_{cr} = \pi^2 EJ/(\mu L)^2 \tag{1}$$

where: $F_{cr}$ – bifurcation force,
$E$ – Young's modulus of the column's material,
$J$ – minimal area moment of inertia of the cross section of the column,
μ – column effective length factor,
$L$ – length of the column.

The $\mu$ factor depends on the boundary conditions. In this study, a case of BC was analyzed, i.e., one end was clamped, so the $\mu$ factor was 2.

First, the length vs. cross-section results obtained for all variants of the eco-composite specimen were analyzed. The analysis showed the same trend for each section tested, i.e., an increase in length would cause the critical load to decrease. According to the theory, the shorter the column, the less susceptible it is to buckling, so the buckling load for such a column must be higher than that required for longer elements, where an increase in their length causes the critical load to decrease, which follows directly from Equation 1.

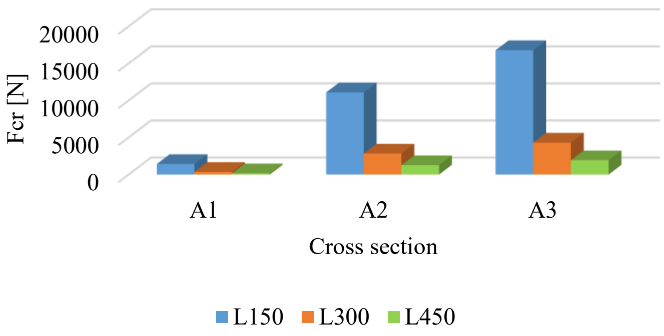



**Fig. 5. Bifurcation loads for different eco-composite samples**

The results obtained for the eco-composite were then compared with those reported for other materials. The results of the comparison are shown in Figure 6, where the relationship between length and critical force is plotted for the smallest cross section A1. All materials show the same trend, i.e. the critical force decreases with length. The forces inducing the first buckling mode in the eco-composite are higher than those observed for LDPE (by 50%) and PE100 (by 12%). For polypropylene (PP), the forces are 123% higher than for the eco-composite. Similar relationships are observed for all lengths tested. The buckling load depends mainly on the Young's modulus(E), which is 123% higher for PP than for the eco-composite.

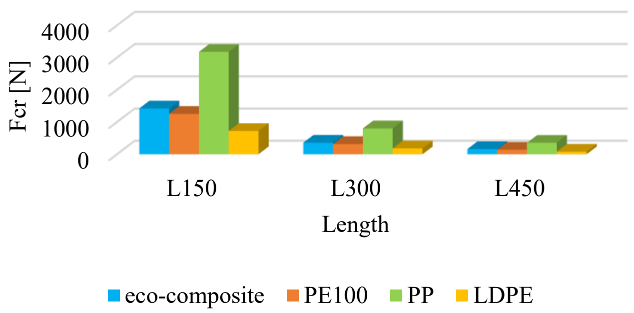



**Fig. 6. Bifurcation loads for A1**

The results obtained for the A2 section are shown in Figure 7, where each material is shown individually and the change in stiffness is plotted as a function of length. The plot clearly shows that the buckling loads for the eco-composite are higher than for the other polyethylene materials.

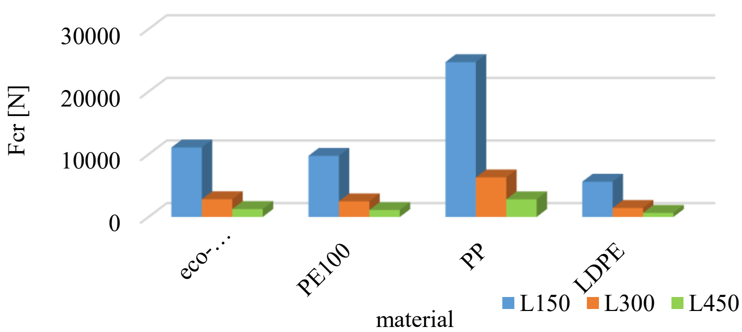



**Fig. 7. Bifurcation load for A2**

Detailed results for all cases tested are shown in Table 3. In the table, the FEM results are compared with the results obtained using Equation 1. The relative error is calculated using the following formula:

$$error = (F_{cr}^{Thy} - F_{cr}^{FEM}/F_{cr}^{Thy}) * 100\% \tag{2}$$

where: $F_{cr}^{Thy}$ – bifurcation force from theory (Eq.1),
$F_{cr}^{FEM}$ – bifurcation force from FEM,

An analysis of the FEM/theory results shows a high agreement between these results (in all cases the relative error was less than 4%). It can also be observed that the agreement between the results is higher for longer beams.

**Tab. 3. Numerical results**

| | **Buckling load [N]** | | | | **A** | **L** |
|---|---|---|---|---|---|---|
| | **Eco-composite** | **PE100 (Ying et al.,2020)** | **PP (Drai et al., 2024)** | **LDPE (Bendarma et al., 2024)** | **mm** | **mm** |
| FEM | 1423.60 | 1254.20 | 3177.70 | 722.30 | | |
| Theory | 1440.23 | 1267.87 | 3213.50 | 730.34 | 40x20 | |
| Error [%] | 1.15 | 1.08 | 1.11 | 1.10 | | |
| FEM | 11087.00 | 9753.10 | 24724.00 | 5620.50 | | |
| Theory | 11521.86 | 10142.97 | 25707.99 | 5842.73 | 40x40 | 150 |
| Error [%] | 3.77 | 3.84 | 3.83 | 3.80 | | |
| FEM | 16781.00 | 14899.00 | 37622.00 | 8528.50 | | |
| Theory | 17282.78 | 15214.46 | 38561.99 | 8764.09 | 40x60 | |
| Error [%] | 2.90 | 2.07 | 2.44 | 2.69 | | |
| FEM | 359.55 | 316.82 | 802.67 | 182.37 | | |
| Theory | 360.06 | 316.97 | 803.37 | 182.59 | 40x20 | |
| error [%] | 0.14 | 0.05 | 0.09 | 0.12 | | |
| FEM | 2825.20 | 2488.30 | 6305.30 | 1432.80 | | |
| Theory | 2880.46 | 2535.74 | 6427.00 | 1460.68 | 40x40 | 300 |
| Error [%] | 1.92 | 1.87 | 1.89 | 1.91 | | |
| FEM | 4307.20 | 3812.20 | 9640.10 | 2187.10 | | |
| Theory | 4320.70 | 3803.61 | 9640.50 | 2191.02 | 40x60 | |
| Error [%] | 0.31 | -0.23 | 0.00 | 0.18 | | |
| FEM | 160.06 | 141.00 | 357.27 | 81.18 | | |
| Theory | 160.03 | 140.87 | 357.06 | 81.15 | 40x20 | |
| Error [%] | -0.02 | -0.09 | -0.06 | -0.04 | | |
| FEM | 1259.90 | 1109.70 | 2811.90 | 638.97 | | |
| Theory | 1280.21 | 1127.00 | 2856.44 | 649.19 | 40x40 | 450 |
| Error [%] | 1.59 | 1.53 | 1.56 | 1.57 | | |
| FEM | 1921.70 | 1698.20 | 4297.30 | 975.53 | | |
| Theory | 1920.31 | 1690.50 | 4284.67 | 973.79 | 40x60 | |
| Error [%] | -0.07 | -0.46 | -0.29 | -0.18 | | |

Finally, the effect of varying the cross-section (A1-A3) and length (L150-L450) on the first mode of buckling and the corresponding critical force is determined, as shown in Figures 8 and 9, respectively. A 100% change in the cross section of the beam (A1-A2) results in a higher stiffness of this structure, which leads to a 685% increase in the buckling load. In contrast, a 50% increase in the A2 cross-section results in a much smaller increase in stiffness, leading to a 53% increase in the critical force. This means that the critical force for A2-A3 is much less sensitive to cross section variation than for A1-A2. A similar trend is observed for all materials and lengths tested. A 100% change in length (L150-L300) results in a 75% decrease in critical force.

On the other hand, a 50% increase in length (L300-L450) causes a 55% decrease in the critical load. The same relationship can be observed for all materials and cross-sections tested.

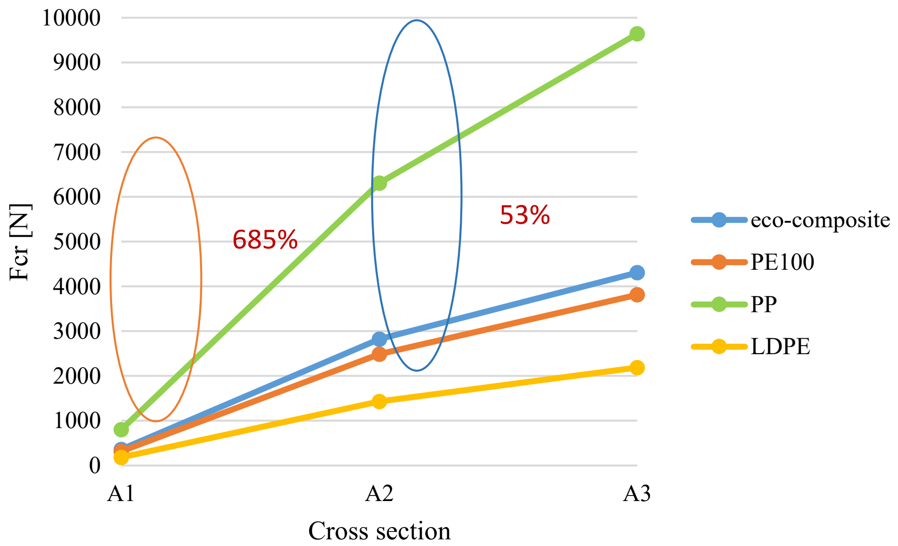



**Fig. 8. Bifurcation load for L300**

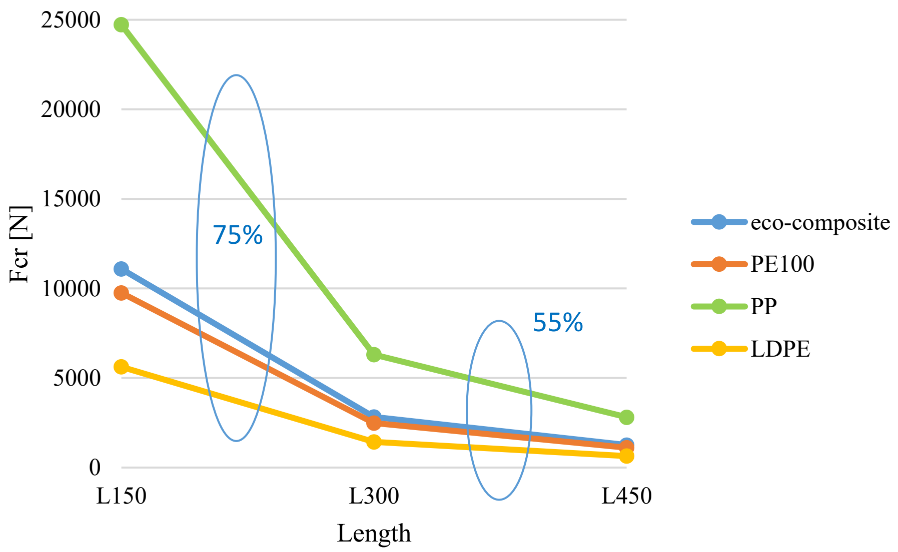



**Fig. 9. Bifurcation load for A2**

## 5. CONCLUSIONS

This paper presents the experimental results of a study investigating a new eco-composite made of 100% recycled material. Tensile tests showed that the stiffness parameters of this eco-composite were higher than those of other materials with similar applications, i.e. LDPE and HDPE. Static tests were performed to determine the first buckling mode and the corresponding critical force. The results obtained were then compared with those reported in the literature for other modern composites, i.e. PE and PP. Three different beam cross sections and three different beam lengths were tested. For each variant tested, the beam was fixed in the same way, i.e. it was clamped at one end. The tests were performed in the Abaqus environment using the finite element method and the analytical method. High agreement was obtained between the results obtained by both methods, i.e. the relative error was less than 4%.

The results of this study showed that the new recycled eco-composite was more effective than LDPE and HDPE due to its higher stiffness and higher critical compressive loads. In addition, it was observed that a 100% increase in the initial rectangular cross-section of $800 mm^2$ resulted in a 685% increase in the stiffness of the beam. When changing the cross-section, the thickness of the structure is an important factor. In each case, the beam buckled in the flexible direction, i.e., at a smaller thickness. Changing the cross section from $16 cm^2$ to $24 cm^2$ resulted in an additional 53% increase in stiffness. Length was found to be another factor that significantly affected the critical force. Buckling occurred earlier (at lower loads) in longer beams, while shortening the beam would make it stiffer and less prone to buckling. Increasing the initial beam length of 150 mm by 100% resulted in a 75% reduction in the critical force. With a beam length of 450 mm, an additional force reduction of 55% was achieved. In summary, changing the thickness of the system at smaller cross-sections has a large effect on the stiffness of the system, while changing the length of the system has a significant effect at a similar level for all variants. It was also found that the eco-composite would retain similar properties to the other materials tested and therefore could be successfully used in engineering structures.

## Funding

*This study was supported by a scientific discipline fund awarded to the Department of Applied Mechanics, Lublin University of Technology, under grant No. FD-20/IM-5/032/2024.*

## Conflicts of Interest

*The authors declare that there is no conflict of interest for this manuscript.*

## REFERENCES

Abaqus HTML Documentation. (n.d.). *Dassault Systèmes*. https://help.3ds.com/current/abaqus/index.html

Bendarma, A., Jankowiak, T., Rusinek, A., Lodygowski, T., Czarnota, C., Bernier, R., & Khalfaoui, M. (2024). Experimental and numerical analysis of aluminum-polyethylene composite structure subjected to tension and perforation under dynamic loading for a wide range of temperatures. *Journal of Dynamic Behavior of Materials*, *10*, 51–74. https://doi.org/10.1007/s40870-023-00400-y

Drai, A., Aour, B., Daikh, A. A., Talha, A., & Eltaher, M. A.(2024). Modeling and finite element simulation of polypropylene behavior under severe plastic deformation by high-pressure torsion. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *46*, 618. https://doi.org/10.1007/s40430-024-05143-y

E-Xstream engineering. (2016). *DIGIMAT - User's manual*. MSC Software Belgium SA, MontSaint-Guibert.

Frącz, W., Janowski, G., & Ryzińska, G. (2017). The possibility of using wood fiber mats in products manufacturing made of polymer composites based on numerical simulations. *Applied Computer Science*, *13*(4), 65-75. https://doi.org/10.23743/acs-2017-30

Gada, D. V. (2024). 3D printing's green revolution: A review of usage of sustainable and recycled polymers. *Material Science Research India*, *21*(3). http://dx.doi.org/10.13005/msri/210302

Głogowska, K., Pączkowski, P., & Samujło, B. (2022). Study on the properties and structure of rotationally moulded linear low-density polyethylene filled with quartz flour. *Materials*, *15*(6), 2154. https://doi.org/10.3390/ma15062154

Głogowska, K., Rozpędowski, J. (2016). Examination of shredding process parameters and the properties of recyclate. *Advances in Science and Technology Research Journal*, *10*(29), 176-179. https://doi.org/10.12913/22998624/61950

Habibi, M., Kazemi Najafi, S. & Ghasemi, I. (2017). Rheological and mechanical properties of composites made from wood flour and recycled LDPE/HDPE blend. *Iranian Polymer* Journal, *26*, 949–956. https://doi.org/10.1007/s13726-017-0579-0

International Organization for Standardization. (2012). Plastics—Determination of tensile properties—Part 1: General principles (ISO 527-1:2012). https://www.iso.org/standard/56045.html

International Organization for Standardization. (2019). Plastics—Methods for determining the density of non-cellular plastics—Part 1: Immersion method, liquid pycnometer method and titration method (ISO 1183-1:2019). https://www.iso.org/standard/74990.html

Müller, M., Kolář, V., Mishra, R. K. (2024). Mechanical and thermal degradation-related performance of recycled LDPE from post-consumer waste. *Polymers*, *16*(20), 2863. https://doi.org/10.3390/polym16202863

Murat, B. I. S., Kamalruzaman, M. S., Nor Azman, M. H., Misroh, M. F. (2020). Assessment of mechanical properties of recycled HDPEand LDPE plastic wastes. *Materials Science and Engineering, 957*, 012046. https://doi.org/10.1088/1757-899X/957/1/012046

Pfaendner, R. (2022). Restabilization – 30 years of research for quality improvement of recycled plastics review. *Polymer Degradation and Stability*, *203*, 110082. https://doi.org/10.1016/j.polymdegradstab.2022.110082

Pimentel Real, L. E. (2023). *Recycled Materials for Construction Applications: Plastic Products and Composites*. Springer International Publishing.

Różyło, P., & Wrzesińska, K. (2016). Numerical analysis of buckling and critical forces in a closed section composite profile. *Applied Computer Science*, *12*(2), 54-62.

Sawa, M., Szala, M., & Henzler, W. (2021). Innovative device for tensile strength testing of welded joints: 3D modelling, FEM simulation and experimental validation of test rig – a case study. *Applied Computer Science*, *17*(3), 92-105. https://doi.org/10.23743/acs-2021-24

Sikora, J. W., Głogowska, K., Majewski, Ł. (2019). Waste from renewable sources as a polyethylene filler. *Materials Science and Engineering*, *600*, 012020. https://doi.org/10.1088/1757-899X/600/1/012020

Teter, A., Kolakowski, Z. (2023). Global buckling of axially functionally graded columns with variable boundary conditions. *Composite Structures*, *304*(Part 2),116430. https://doi.org/10.1016/j.compstruct.2022.116430

Teter,A., Kolakowski, Z. (2024). Susceptibility versus flexural stiffness in the stability of hybrid laminate columns with a rectangular cross section for a 1D model. *Composite Structures*, *345*, 118362. https://doi.org/10.1016/j.compstruct.2024.118362

Ying, W., Xiao, Y., Sixi, Z. (2020). Mechanical behavior analysis of buried polyethylene pipe under land subsidence. *Engineering Failure Analysis*, *108*, 104351. https://doi.org/10.1016/j.engfailanal.2019.104351