BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Volumul 68 (72), Numărul 3, 2022
Secţia
CONSTRUCŢII DE MAŞINI
DOI:10.2478/bipcm-2022-0022

DESIGN AND TESTING OF MULTI-MATERIAL SHAPE-CHANGING FLEXURE HINGES FOR FUSED FILAMENT FABRICATION

BY

VASILE ERMOLAI[1,2,*], GHEORGHE NAGÎŢ[1], ALEXANDRU SOVER[2] and IOAN SURUGIU[1]

[1]“Gheorghe Asachi” Technical University of Iaşi, Department of Machine Manufacturing Technology, Blvd. D. Mangeron, 59A, 700050 Iaşi, Romania
[2]Ansbach University of Applied Sciences, Faculty of Technology, Residenzstraße 8, 91522 Ansbach, Germany

Received: June 28, 2022
Accepted for publication: July 25, 2022

Abstract. Living hinges are non-assemblable flexible joints that allow the relative rotation of two adjacent rigid parts through bending. Conventionally, living hinges are single-material designs made through injection moulding, for example. In order to reduce mould complexity, flexure hinges have a restrictive design. However, 3D printing technologies, such as Fused Filament Fabrication - FFF, can provide new opportunities for hinge development, allowing more design freedom and a wide range of materials. This paper focused on exploring and testing various multi-material hinges designs with bidirectional folding made of compatible and low-compatible thermoplastic materials. The resulting designs have corrugated structures and shape-changing interfaces, each with multiple solutions. They were printed as samples made of acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) for the rigid bodies and with thermoplastic co-

*Corresponding author; *e-mail*: vasile.ermolai@student.tuiasi.ro
© 2022 Vasile Ermolai et al.
This is an open access article licensed under the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0).

polyesters (TPC) for the hinge. The results show that corrugated and shape-changing structures can be used as a design solution for flexure hinges.

Keywords: Multi-material hinge, Two-way folding, Corrugated structure, Shape-changing interfaces, Fused Filament Fabrication.

1. Introduction

Compliant mechanisms are systems that use the flexibility of their components to attain motion, and living hinges are such components (Howell, 2013). Flexure hinge design starts from a blank piece thinned by at least one cut-out in the middle plane. The resulting structure is a narrow beam connecting two adjacent bodies (Liu *et al.*, 2017). Injection moulding can be used to manufacture living hinges. When designed correctly, they can surpass one million folding cycles (Balderrama-Armendariz, 2019). An example of a regular flexure hinge before and after folding is presented in Fig. 1.

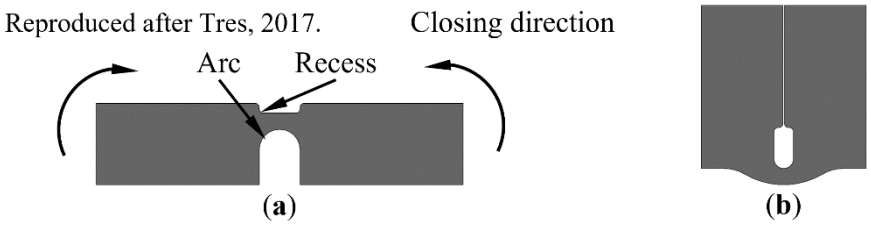


Fig. 1 − Living hinge design for PP and PE: (**a**) before and (**b**) after bending 180°.

3D printing offers new opportunities for product development, and the living hinge is one of them. However, most designs refer to non-symmetrical hinges with unidirectional folding (see Fig. 1). Multiple researchers studied the performance of the same hinge design printed with the same materials (*e.g.*, thermoplastic polyurethane-TPU, but the results differ due to the distinct testing methods (Lussenburg *et al*., 2021). Multi-material FFF can extend living hinge development by using elastomers for the folding element. Using a geometrical contact interface (Ribeiro and Carneiro, 2019) between the hinge and the rigid bodies, materials choice can be eased as compatibility is no longer an issue.

This paper explores the various flexure hinges designed for two-way folding. This way, the study aims to investigate if FFF 3D printing can be used for reliable flexure hinge fabrication. The resulting designs focus on hinges with corrugated structures and hinges with shape-changing interfaces. Nine design solutions were printed using compatible (*i.e.*, ABS-TPC) and low-compatible (*i.e.*, PLA-TPC) materials. The resulting specimens were tested for tensile strength. The results show that hinge design and printing environment influence the hinge performance.

2. Methods

The specimens' design focused on hinges with corrugated, shape-changing interfaces. A macroscopic interface was considered to compensate for materials' low compatibility (*i.e.*, PLA-TPC).

The contact geometry was designed for a custom test sample concerning the design rules for FFF (Djokikj *et al.*, 2022). The resulting specimen design is presented in Fig. 2.

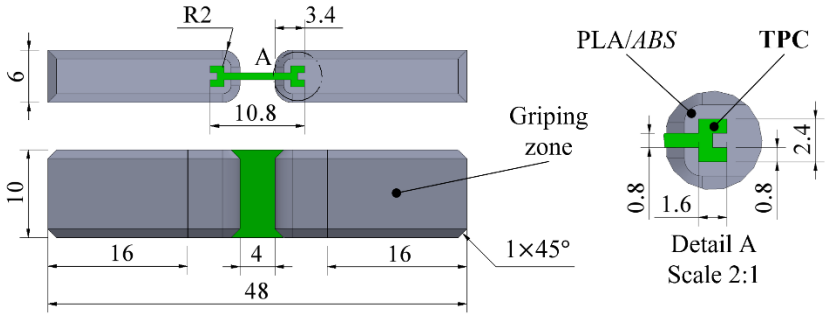


Fig. 2 − Two-way folding hinge test sample definition for tensile test.

Corrugated profiles are obtained by shaping a simple flat surface into parallel grooves uniformly spread to form a symmetrically wavy surface. Based on their use (*e.g.*, sandwich panel cores, sheet metal panels), the corrugated profiles can have various shapes such as V-shape, I-shape, C-shape, sinusoidal shape, and many more (Feng *et al.*, 2020; Xiong *et al.*, 2019, San Ha and Lu, 2020). A part of those profiles could be suitable for two-way folding hinges. Due to their corrugated structure hinge's neutral fibre length can be augmented within the same gap between the rigid bodies. This can provide an increase in the folding allowance. Three corrugated profiles were designed for the custom samples, having a hat-shape, V-shape, and arc circle shape. The resulting geometries and their constructive constraints are presented in Fig. 3.

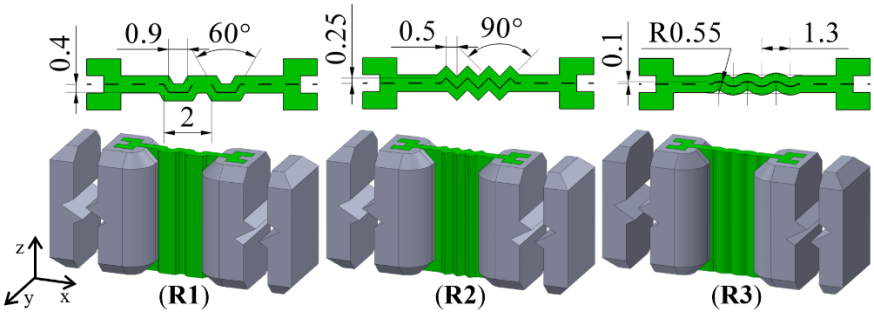


Fig. 3 − Dimetric view of two-way folding hinges with open profile corrugated structures: (**R1**) hat-shaped profile; (**R2**) V-type profile; (**R3**) arc profile.

The shape-changing interfaces are compliant mechanisms capable of changing their shape when folded. CO_2 laser applications in plywood cutting inspired these hinges' design. By performing thin cuts of a specific geometry (*e.g.*, parallelogram, cross, Arabic pattern) in a wood piece and with a defined pattern on the entire piece width, the resulting product can change its shape through bending. Based on the cut-out profile and distribution, one or more degrees of freedom can be achieved (Jasen *et al.*, 2017; Ziga *et al.*, 2018).

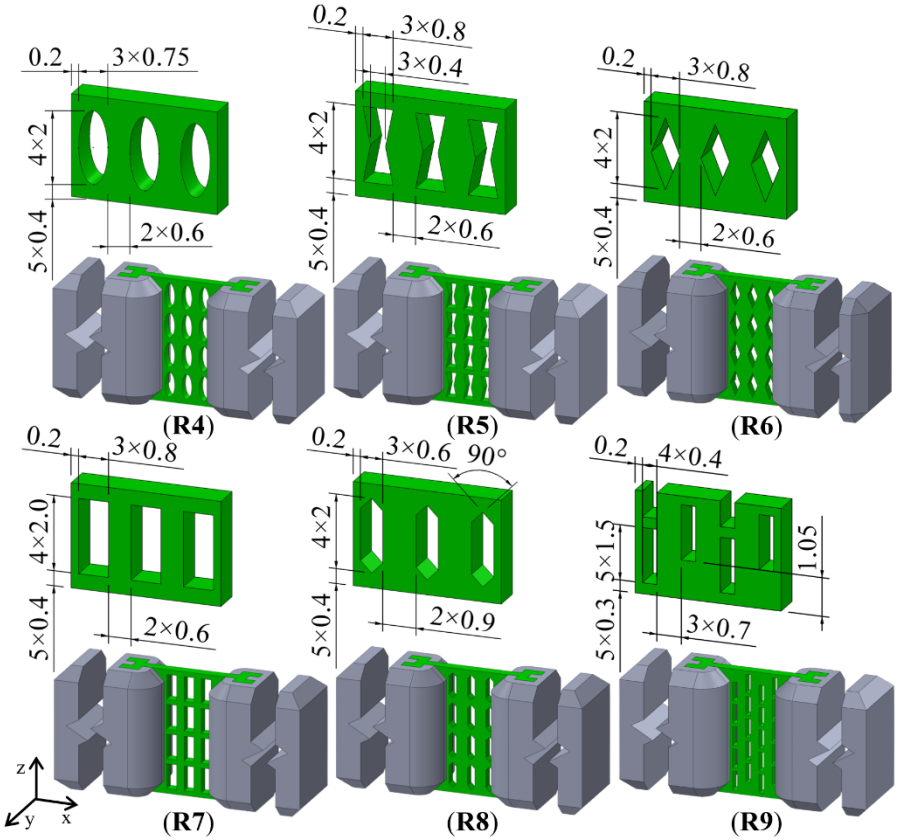


Fig. 4 − Dimetric view of hinges with shape-changing interfaces: (**R4**) elliptical; (**R5**) hourglass, (**R6**) rhomboid; (**R7**) rectangular; (**R8**) rectangular with 45° chamfers, (**R9**) rectangular with an asymmetrical linear pattern.

For this study, six shape-changing interfaces were considered. Each cut-out profile and ist' linear pattern distribution is shown in Fig. 4. Because the hinge's material has a 45D shore hardness (*i.e.*, a hard rubber), it bends relatively difficultly. The premise was that by performing the cut-outs in the hinges' bodies (Fig. 4), the resulting designs would have an improved bendability compared to the corrugated structures.

Both hinges design categories, presented in Fig. 3 and Fig. 4, were designed for two passes of the extrusion head and a line width of 0.4 mm.

Two materials were chosen for the specimens' bodies, a PLA from 3Dimensionals and an ABS from REC. An Innoflex 45D TPC material from BASF was selected for the hinges. The g-code files were made using Cura 4.13.0 and produced on an Ultimaker 3 FFF printer using an 0.4 mm nozzle. Each design was printed with four replicates with the same configuration (*e.g.*, layer height). Because of the different melting ranges and flow behaviour of the considered materials, parametrization must be done for each material separately (Ermolai *et al.*, 2022). For the TPC, the resulting materials parameter values (*e.g.*, retraction distance, printing speed) were determined by trials (Table 1).

Table 1
Printing process parameters

Parameter	PLA/*ABS*/**TPC**	Parameter	Value
Extrusion temperature (°C)	215/*245*/**240**	Layer thickness (mm)	0.15
Bed temperature (°C)	60/*90*/**60**	Extrusion width (mm)	0.4
Print speed (mm/s)	30/30/**5**	No. of perimeters	3
1st layer speed (mm/s)	15/*15*/**5**	No. of top/bottom layers	6
Retraction distance (mm)	7/7/**4**	Infill pattern	Gyroid
Retraction speed (mm/s)	35/*35*/**40**	Infill density (%)	10
Fan speed (%)	100/*0*/**25**	Brim	Yes
Closed environment	No/*Yes*/**No**	Brim width (mm)	3
Values in Italic refer to ABS material; **Values in Bold refer to TPC material.**			

After printing, the hinges were tested for tensile strength to evaluate the influence of the design influence over the layer bond formation. The samples were tested using an Instron 4411 universal machine at 10 mm/s speed. The laboratory conditions were 22°C with 62% moisture. The average results were used to evaluate the design of the hinges.

3. Results and discussion

The samples were evaluated for hinge quality before and after folding. Thus, the resulting hinges' print quality was assessed based on the layers' consistency and shape compared to the CAD model, followed by hinge deformation after bending.

3.1. Hinges with corrugated structure

The corrugated structure hinges presented a good print quality of the samples for both groups of materials, PLA-TPC and ABS-TPC (see unfolded

samples in Fig. 5). The resulting specimens respect CAD models specification showing minimum stringing (*i.e.*, hair-like artefacts) and acceptable first-layer horizontal expansion (see the side view of the unfolded hinges in Fig. 5). However, after folding, the TPC layers from the PLA-TPC group delaminated and showed multiple cracks or complete detachment of the flexure hinge. Withal, the second group, printed with ABS material for the rigid bodies, the TPC hinge did not fail. The integrity of the hinge was maintained even after one folding (Fig. 5). A possible explanation is given by the different printing conditions of the two materials' configurations. Due to the ABS material sensitivity to environment temperature variation, the ABS-TPC samples were printed in a closed environment (see Table 1) having a constant temperature of 40°C. This way, the TPC cooling speed was slowed, resulting in an improved layer fuse.

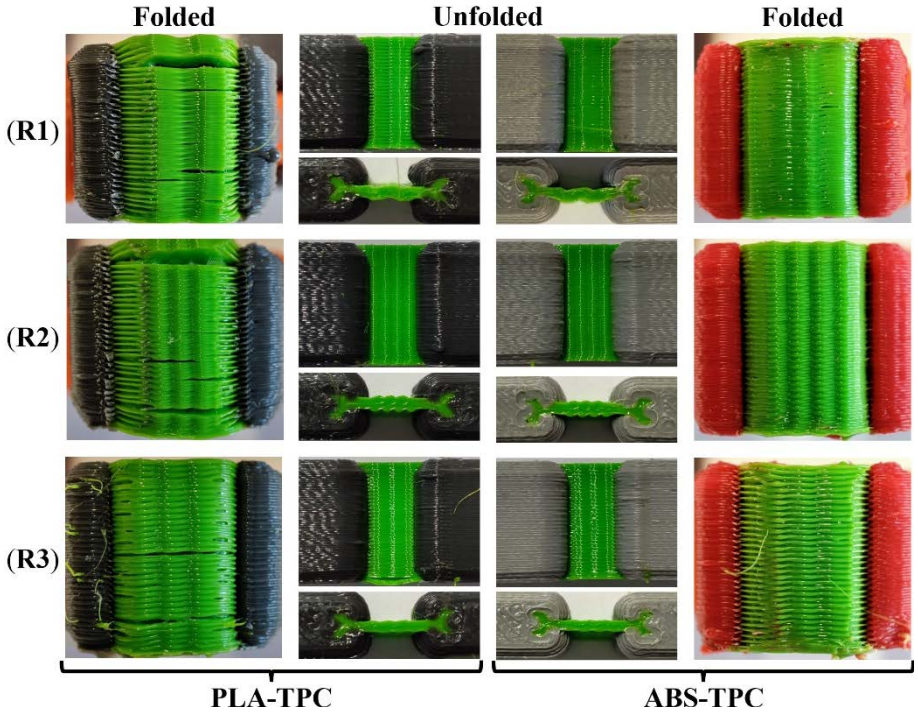


Fig. 5 − Print samples of two-way folding hinges with open profile corrugated structures and macroscopic interlocking interface: (**R1**) trapezoidal profile; (**R2**) triangular profile; (**R3**) arc-tangent profile.

Regarding the tensile test, all specimens presented a similar failure mode between each group of materials. The hinge' layers were delaminating for the PLA-TPC samples as the clamping dies moved, resulting in a batch of

strings held only by the macroscopic contact interface with the rigid bodies. On the other hand, in the second group, ABS-TPC, due to the better layer fuse, the delamination degree was considerably smaller compared to the previous. A sample of tensile trial results and the failure mode of each material pair is presented below, in Fig. 6.

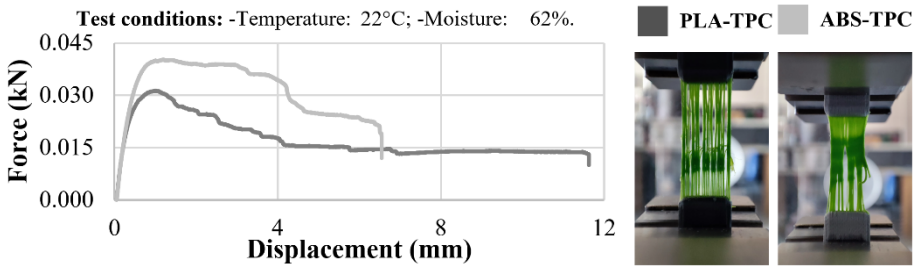


Fig. 6 – Force-displacement curve of the R3 hinges and their failure mode.

Interestingly, even if layer delamination affected PLA-TPC samples, the average load capacity was not affected significantly compared to the ABS-TPC. As presented in Fig. 7, the PLA-TPC samples showed a small variation in the maximum force compared to the ABS-TPC specimens. Similar behaviour was registered for the displacement and higher variation between the materials groups. Overall, the best resulting corrugated structure was the R3 configuration, with an arc tangent profile. The average tensile test results for each hinge design and material configuration are presented in Fig. 7.

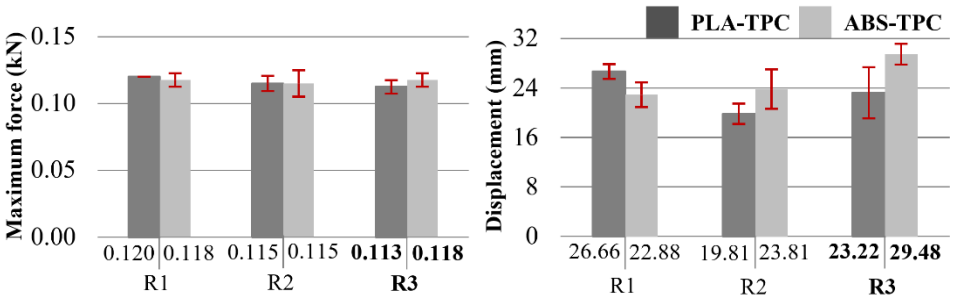


Fig. 7 − Average force and displacement for the hinges with the corrugated profiles.

3.2. Hinges with shape-changing interfaces

The hinges with shape-changing interfaces presented a satisfying print quality of the specimens, considering the small feature size of the cut-outs (see Fig. 4). The resulting specimens respect CAD models but with a considerable level of filament stringing, as presented in Fig. 8. As previously,

the closed printing environment influenced hinges' print quality. In the same figure, it can be observed that PLA-TPC samples (*i.e.*, printed in an open environment) show a better quality of the hinges, with less material stringing and better cut-outs profile accuracy than the ABS-TPC samples (see Fig. 8-R4).

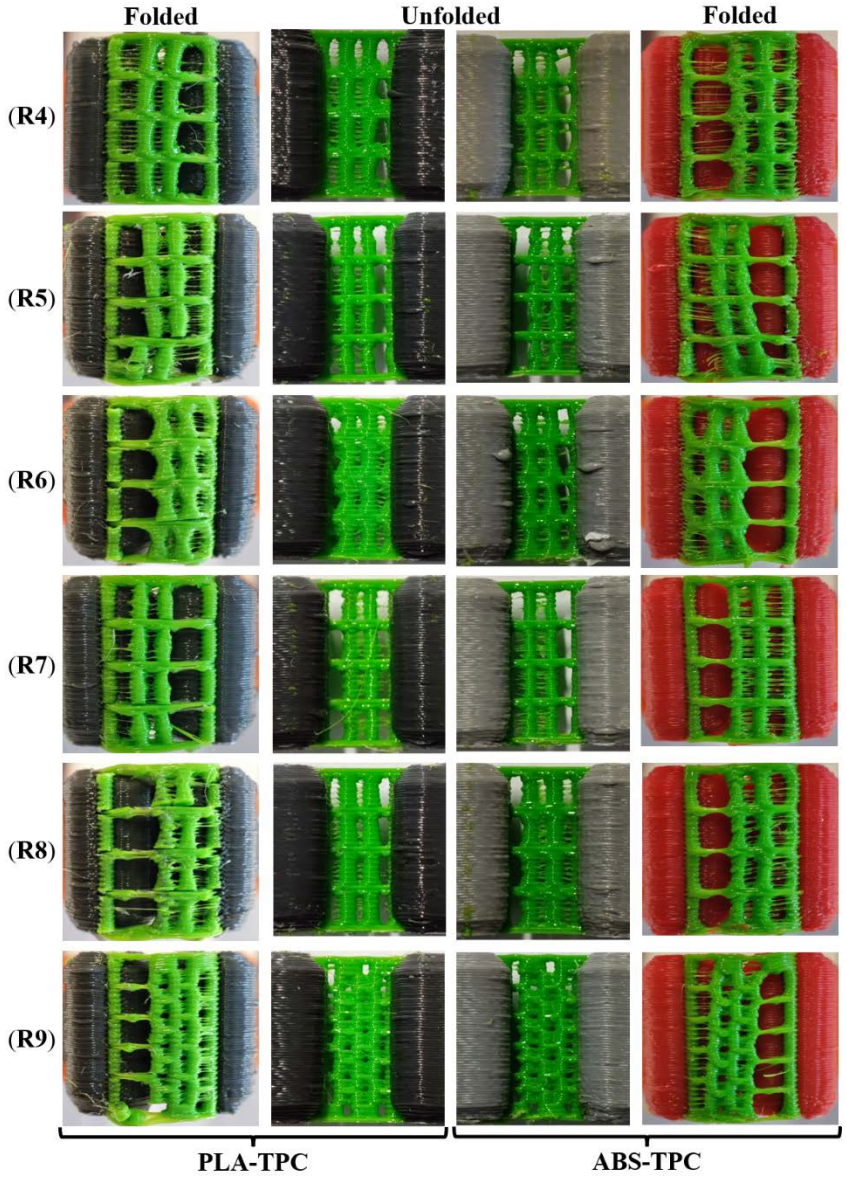


Fig. 8 − Print results of the hinges with shape-changing interfaces: (**R4**) elliptical; (**R5**) hourglass; (**R6**) rhomboid (**R7**) rectangular; (**R8**) rectangular with 45° chamfers; (**R9**) rectangular with asymmetrical linear pattern.

After bending, the hinge layers from the PLA-TPC samples were delaminated and showed multiple cracks at the boundary between PLA and TPC or complete detachment of the hinges' features (see Fig. 8-R5, Fig. 8-R8).

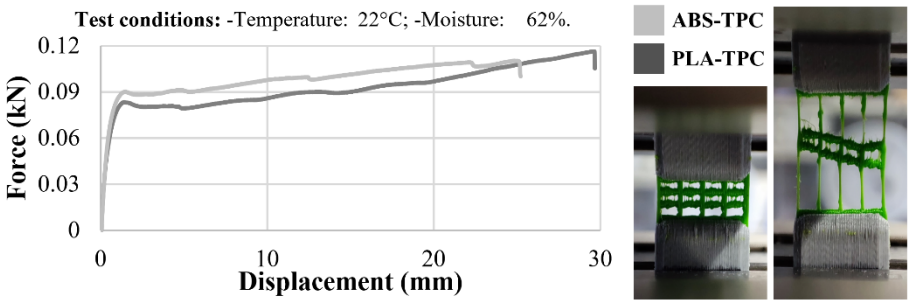


Fig. 9 – Force-displacement diagrams of the R6 hinges; the ABS-TPC sample before and after tensile test.

Due to the constructive cut-outs, the cross-sectional areas of the hinges were decreased, resulting in five to six thin beams connected by the remaining material. The resulting force and displacement values were significantly reduced compared to the hinges with corrugated structures. Overall, the best results were obtained for the configuration of the ABS-TPC materials. A sample of the R6 design results and failure mode is shown in Fig. 9.

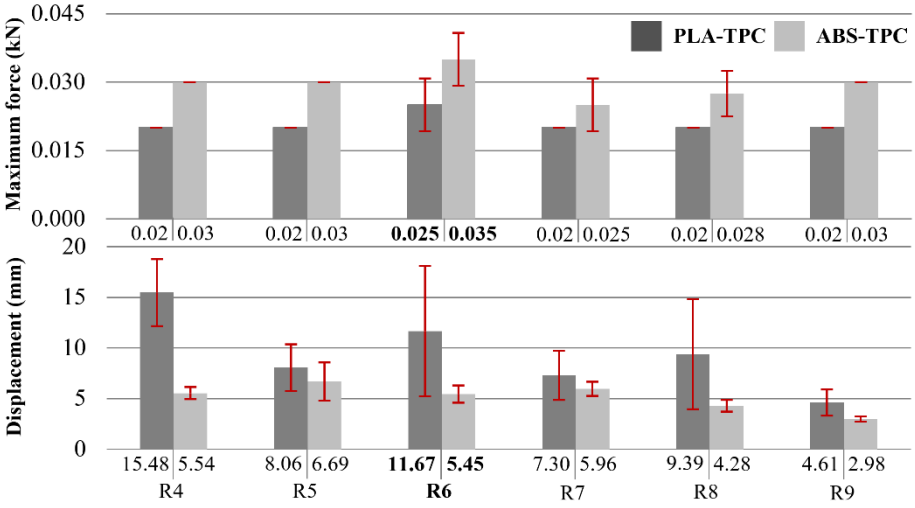


Fig. 10 − Average force and displacement for the hinges with shape-changing interfaces.

As presented in Fig. 10, the PLA-TPC samples recorded lower load capacity than the ABS-TPC specimens, with the maximum force variation in the range (0.08, 0.1). On the other hand, higher variations between the materials groups were recorded for the displacement. It can be observed that the PLA-TPC configurations show higher displacements compared to the ABS-TPC. The printing environment is influencing the bridging quality of the print. If combined with a slow cooling degree of the materials (see Table 1) and a closed printing environment, this could lead to the poorer print quality of the bridged material (see Fig. 8). Those printing conditions could explain the results of the displacement. The best resulting shape-changing interface was the R6 configuration, with a rhomboid pattern printed in ABS-TPC set-up.

4. Conclusions

Multi-material FFF introduced new possibilities regarding living hinge design. Multi-material flexure hinges can be produced in compatible and low-compatible materials configurations using a geometrical contact interface.

Hinges with corrugated structures have proven to be a good solution for functional applications, showing a satisfying load capacity even after high deformations. Although the manufacturing conditions between the samples were different, results show minor variations in the mechanical properties. This indicates that the geometrical interlocking approach is feasible for practical use.

The laser-cut plywood hinges inspired the hinges with shape-changing interfaces. Even if the constructive cut-outs significantly decrease the mechanical properties, the folding is improved. Larger scale specimens should be tested to limit the influence of minimum feature size for FFF.

Printing conditions influence the folding mechanism and failure mode of the hinges. A closed printing environment enhances layers fuse. Regarding the hinge's design, the arc tangent profile shows the best mechanical profile for corrugate structures. As for the hinges with shape-changing interfaces, future work needs to be done to find an optimal cut-out pattern for FFF 3D printing.

REFERENCES

Balderrama-Armendariz C.O., MacDonald E., Roberson D. *et al*., *Folding behavior of thermoplastic hinges fabricated with polymer extrusion additive manufacturing*, Int. J. Adv. Manuf. Technol., **105**, 233-245, (2019).

Djokikj J., Kandikjan Mircheski I., *Design Recommendations for FFF Parts*, Int. Conf. on Machine and Ind. Design in Mech. Eng, KOD 2021, Novi Sad, Serbia, 2022, 237-247.

Ermolai V., Sover A., Nagîț G., *Strength Characterization of Dissimilar Material Samples Produced via Fused Filament Fabrication*, Nonconventional, Technologies Review, **26**(1), (2022).

Feng Y., Qiu H., Gao Y., Zheng H., Tan J., *Creative design for sandwich structures: A review*, Int. J. of Adv. Robot. Sys., 1-24, (2020).

Howell L.L., *21st Century Kinematics. Springer-Verlag*, London, 189-216, 2013.

Jasen M.B., Blindheim J., Steinert M., *Prototyping shape-changing interfaces - An evaluation of living hinges' abilities to resemble organic, shape-changing interfaces*, Proc. of the 21st Int. Conf. on Eng. Design, ICED17, 2017, Vancouver, Canada, **4,** 287-296.

Liu M., Zhang X., Fatikow S., *Design and analysis of a multi-notched flexure hinge for compliant mechanisms*, Precision Eng., **48**, 292-304, (2017).

Lussenburg K., Sakes A., Breedveld P., *Design of non-assembly mechanisms: A state-of-the-art review*, Addit. Manuf. J., **39**, 101846, (2021).

Ribeiro M., Carneiro O.S., *Interface geometries in 3D multi-material prints by fused filament fabrication*, Rapid Prototyp. J., **25**(1), 38-46, (2019).

San Ha N., Lu G., *Thin-walled corrugated structures: A review of crashworthiness designs and energy absorption characteristics*, Thin-Walled Struct., **157,** 106995, (2020).

Tres A.P., *8th Designing Plastic Parts for Assembly*, Carl Hanser Verlag, Munich, 219-260, 2017.

Xiong J., Du Y., Mousanezhad D., Eydani Asl M., Norato J., Vaziri A., Sandwich Structures with Prismatic and Foam Cores: A Review, Adv. Eng. Mater. **21**, 180036, (2019).

Ziga A., Begić-Hajdarević D., Cogo Z., *Mechanical toys and souvenirs obtained by CO_2 laser cutting of plywood*, 13th Int. Sci. Conf. MMA-Flexible Technologies, 2018, Novi Sad, Serbia.

PROIECTAREA ȘI TESTAREA DE BALAMELE FLEXIBILE MULTIMATERIAL CU SCHIMBAREA FORMEI PENTRU FABRICAȚIA CU FILAMENT FUZIBIL

(Rezumat)

Balamalele flexibile sunt îmbinări nedemontabile care permit rotirea relativă a două componente rigide adiacente prin îndoire. În practică, balamalele flexibile sunt realizate dintr-un singur material prin procese de injectare în matriță. Pentru a reduce complexitatea matrițelor balamale flexibile au de obicei un design restrictiv. Cu toate acestea, tehnologiile de tipărire 3D, precum Fabricația cu Filament Fuzibil (FFF), conferă noi posibilități de dezvoltare ale balamalelor, datorită libertății de exprimare în

proiectarea constructivă și a paletei largi de materiale. Această lucrare se concentrează pe proiectarea și testarea a mai multor variante constructive de balamale multimaterial bidirecționale, realizate din materiale termoplastice compatibile și cu compatibilitate redusă. Soluțiile rezultate au structuri ondulate și structuri capabile de schimbarea formei. Acestea au fost tipărite sub formă de epruvete utilizând acrilonitril butadien stiren (ABS) și acid polilactic (PLA) pentru corpurile rigide și un co-poliester termoplastic (TPC) pentru balama. Rezultatele obținute arată că ambele variante constructive, structuri ondulate și cu schimbare a formei, pot fi utilizate ca soluții pentru balamalele flexibile.