An Analysis of the Structural Properties of 3D Printed Square Blocks Prepared using Sustainable Thermoplastic Polyurethane (TPU) Material

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Abstract. For a wide range of utilization, 3D printing is a swiftly developing technology that demands meticulous evaluation of materials, production speed, and resolution. Significant outcomes have been obtained from the application of 3D technology in Cultural Heritage (CH) protection, the valorisation process, communication, and asset incorporation; this is especially true of interdisciplinary initiatives including manufacturing engineering, computer-generated records, and CH accessibility. The primary factors influencing the layout and choosing materials for additive manufacturing are applicability and fabrication technique. A wide range of materials, comprising ceramics and metals, hydro-gels, thermoplastic substances and combinations of these substances, can be used. This study investigates the design and fatigue analysis of a 3D-printed square block made of thermoplastic polyurethane (TPU) under various test conditions, including static structural analysis for compression, fatigue analysis and total deformation within the block layer. The uniform stress distribution was also discussed in detail, as well as the design life and safety factors of the block under fatigue conditions, with its natural frequencies observed in experimental results adjusted the printing parameters for and maintained the process to ensure the best output quality. Post-publication steps included detailed analysis and mechanical testing to verify mechanical properties and dimensional accuracy.

Keyword-: 3D printing, TPU, square blocks, CFD simulation, manufacturing.

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1 Introduction

Additive manufacturing, commonly referred to as 3D printing, is an evolving technology that uses computer-aided design (CAD) models to produce huge numbers of physical objects from dimensional models in a variety of industries, which includes medical services, the agricultural sector, automobile manufacturing, and aerospace [1-4]. One common technique for producing intricate geometric patterns is 3D printing, which provides precise, affordable, and adaptable results [5-7]. Direct digital production is made possible by 3D printing, which does away with the requirement for dies or molds in contrast to conventional manufacturing processes like casting, forging, machining, and injection molding [8-11]. The additively layered method does away with the need for assembly by combining several parts into one unit. As patents expire, more affordable desktop computers are becoming available, allowing businesses to produce sophisticated parts for automobiles, jet engines, and medications [12]. When most people hear the word printer, they often picture a standard printer that they may use to print messages and pictures on paper at home or at work. These printers use the dimensions length and breadth to print in a two-dimensional (2D) flat area [13]. In addition to using length and breadth, a three-dimensional (3D) printer adds depth to the print. To put it another way, a three-dimensional (3D) printer is a device for manufacturing that uses additive manufacturing, which adds layer upon layer of material, to manufacture real-world products from a 3D model design [14]. Depending on the printer's size, 3D printouts may be practically anything. Three-dimensional prints can be fused or connected together to create bigger things once the original printing process is finished [15]. Composite products, smart materials, electronic materials, ceramics, and biomaterials are examples of recent material advancements. Since 3D printing systems are flexible and integrated into multi-process systems, they can be used to address a variety of needs related to product requirements and new material development [16-20]. A particular kind of this kind of manufacturing process is the 3D printer, which builds a tangible 3D item by layer upon layer of material addition. This is not the same as consolidation techniques, which take smaller components, combine them, and fuse them to make the intended thing, or the process of subtractive manufacturing, which creates an object by taking material away from resources already in place [21-25].

Using digital files as a starting point, 3D printing technological advances [26-28] is an additive manufacturing method that produces three-dimensional, physical items [29]. Using a 3D printer, layers of material are produced throughout this process until a whole item is created [30]. Compared to traditional manufacturing methods [31-33], 3D printing allows for the production of even complicated geometries with less material waste [344]. This work's primary goal is to examine the square block's compression strength, durability under fatigue and safety factor in preparation for 3D printing with thermoplastic polyurethane (TPU) materials [35].

2 Methodology of 3D Printing Block Printing

In the present work finite element analysis have been conducted on Simple structure of square block with dimensional parameter 25 mm x 25 mm x 25 mm, this FEM analysis includes compression test using static structural analysis, fatigue analysis and model analysis. The total deformation and equivalent stress layer wise have been found by compression test, whereas the design life and safety factor of the material is determined by the fatigue analysis and the natural frequency of the square block has been found in the modal analysis.

In the design phase, specifications and dimensions for the square blocks were meticulously determined, followed by the creation of a precise digital 3D model using CAD software as shown in Fig. 1, ensuring compatibility with 3D printing and suitability for TPU material.

Material selection favored Thermoplastic Polyurethane (TPU) filament for its exceptional flexibility, durability, and resistance to abrasion.

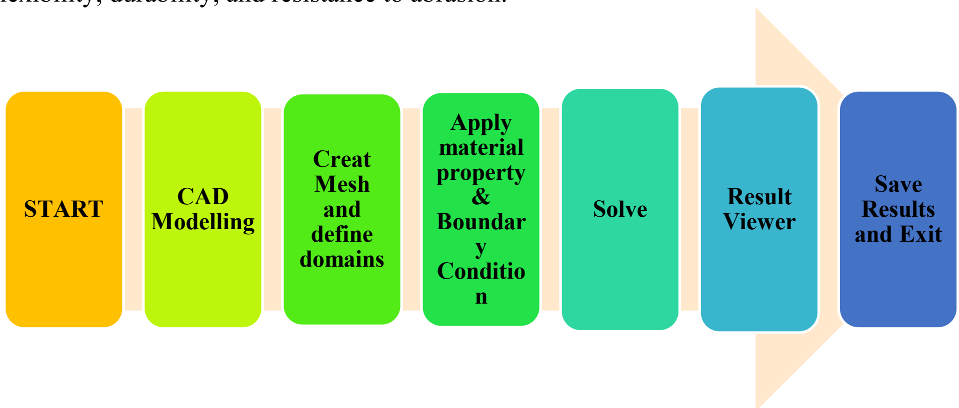

Fig. 1: Algorithm used for Finite element analysis of Structural and fatigue analysis

The preparation of the 3D printer involved precise calibration and the setting of printing parameters tailored to TPU characteristics. As the printing commenced, close monitoring ensured proper layer adhesion and minimal warping, common with TPU. Post-processing involved careful removal of the printed blocks, trimming excess material, and meticulous inspection for defects. Subsequent testing and quality assurance procedures evaluated mechanical properties and dimensional accuracy, while documentation and analysis comprehensively captured the entire process and performance metrics, guiding future improvements and research avenues. A 3D model must be created with a computer program, before a 3D print can begin. Once the model is completed, it is exported into a file format compatible with slicing programs. Slicing software then generates instructions for the printer (G-code) on how to construct the model layer by layer based on the STL file. It may be necessary to post-process the model to achieve the desired finish after the printing process is complete.

3 Result and Discussion

In the present work finite element analysis have been conducted on Simple structure of square block with dimensional parameter 25 mm x 25 mm x 25 mm, this FEM analysis includes compression test using static structural analysis, fatigue analysis and model analysis. The total deformation and equivalent stress layer wise have been found by compression test, whereas the design life and safety factor of the material is determined by the fatigue analysis and the natural frequency of the square block has been found in the modal analysis. For the compressive test perform structural analysis by keep lower side fixed and apply a compressive load of 12200 N on top layer of the square block. Check fatigue life and safety factor by using fatigue tool and for the natural frequencies need to perform model analysis with six possible modes.

3.1 Structure analysis of square block for TPU at 12200 N applied in vertical direction

Total deformation Analysis -: When a material is subjected to an external force, its shape, size, or volume changes completely. This is called total deformation. Deformations of this type include stretching, compressing, bending, or twisting, all of which alter the material's original form. After performing compression test structural analysis on square block for TPU at 12200 N applied in vertical direction, the total deformation of 0.0884 mm has been observed. After performing compression test structural analysis on square block for TPU at 12200 N applied in vertical direction, the equivalent stress ranging from 34.406 MPa at outer layer to 23.338 MPa of at middle layer of square block has been observed and presented in Table 1.

Table 1: Comparative analysis of square block for TPU at 12200 N applied in vertical direction

Parameter	Description	Minimum Value	Maximum Value
Total Deformation	Deformation under vertical load (mm)	0 mm	0.088439 mm
Fatigue Life	Cycles until failure under load	6.06525E+5 cycles	1E8 cycles
Safety Factor	Factor of safety against fatigue failure	0.61452	4.6821

Fatigue Life analysis -: Material science and engineering use fatigue life analysis as a tool to evaluate the durability of materials under cyclic loading conditions. This method is used to determine how long an object or material can withstand repetitive stress before failing as a result of fatigue. After performing fatigue analysis on square block for TPU at 12200 N applied in vertical direction, the minimum fatigue life of 6.065E+5 number of cycles until the part will fail due to fatigue at the corner of the square block has been observed. After performing fatigue analysis on square block for TPU at 12200 N applied in vertical direction, the minimum safety factor of 0.6145 with respect to a fatigue failure at a given design life at the corner of the square block has been observed. Values less than one indicate failure before the design life is reached

3.2 Structure analysis of square block for TPU at 12200 N applied in horizontal direction

Total Deformation-: In terms of total deformation, it is the displacement that occurs as a result of applying horizontal force to a block in relation to its original shape. After performing compression test structural analysis on square block for TPU at 12200 N applied in horizontal direction, the total deformation of 0.0885 mm has been observed. After performing compression test structural analysis on square block for TPU at 12200 N applied in horizontal direction, the equivalent stress ranging from 46.933 MPa at bottom layer to 20.196 MPa of at top layer of square block has been observed and presented in Table 2

Table 2: Comparative analysis of square block for TPU at 12200 N applied in horizontal direction

Parameter	Description	Minimum Value	Maximum Value
Total Deformation	Deformation under horizontal load (mm)	0 mm	0.088488 mm
Fatigue Life	Cycles until failure under horizontal load	7.8125E+5 cycles	1E8 cycles
Safety Factor	Factor of safety against horizontal fatigue failure	0.62964	4.7973

Fatigue analysis-: In this context, fatigue life analysis measures how long it takes the TPU block to fail after repeated horizontal loads. After performing fatigue analysis on square block for TPU at 12200 N applied in horizontal direction, the minimum fatigue life of 7.8125E+5 numbers of cycles until the part will fail due to fatigue at the corner of the square block has been observed.

Safety Factor -: A safety factor serves primarily as an accounting tool for uncertainties in the design and manufacturing process, variations in material properties, unanticipated loads, degradation over time, and inaccuracies in analysis. By protecting the structure from potential failure, it increases its reliability and safety.
After performing fatigue analysis on square block for TPU at 12200 N applied in horizontal direction, the minimum safety factor of 0.6296 with respect to a fatigue failure at a given design life at the corner of the square block has been observed. Values less than one indicate failure before the design life is reached. After performing fatigue analysis on square block for TPU at 12200 N applied in horizontal direction, the minimum available life of 7.8125E+5 cycle on Log-Log scaling with respect to a fatigue failure at a given design life.

4 Comparative results

4.1 Total deformation at vertical loading for 3D printed Square block made of TPU material

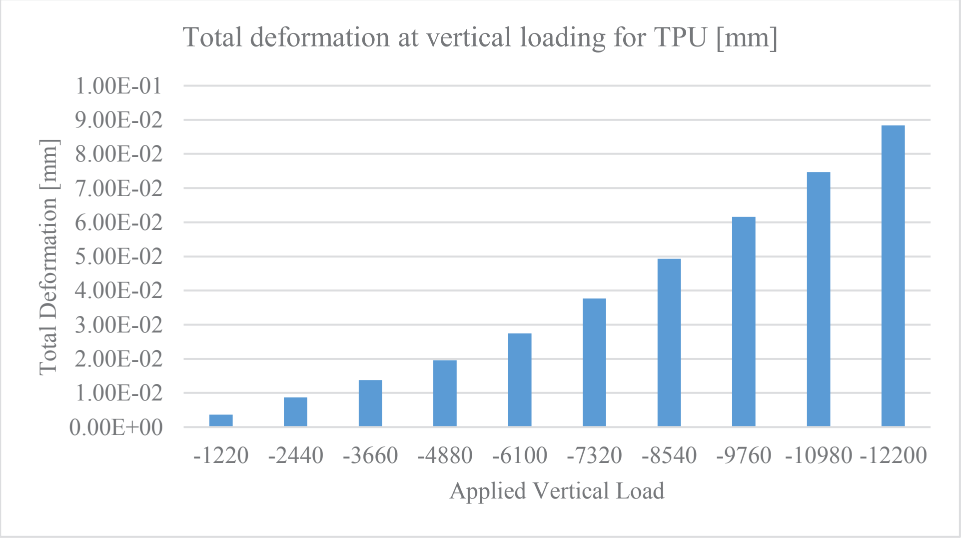

Fig. 2: Total deformation at vertical loading

According to the graph in Fig. 2, thermoplastic polyurethane (TPU) experiences total deformation when subjected to vertical loading. There are eleven different instances or samples plotted for deformation values. There is a general trend of increasing deformation across samples beginning at a relatively low value. Deformation reaches its maximum at sample 11, just under 0.1 mm, which is the highest value observed. If these are findings from repeated testing, the sequential order of loading might affect the TPU's deformation depending on the magnitude and type of vertical load applied.

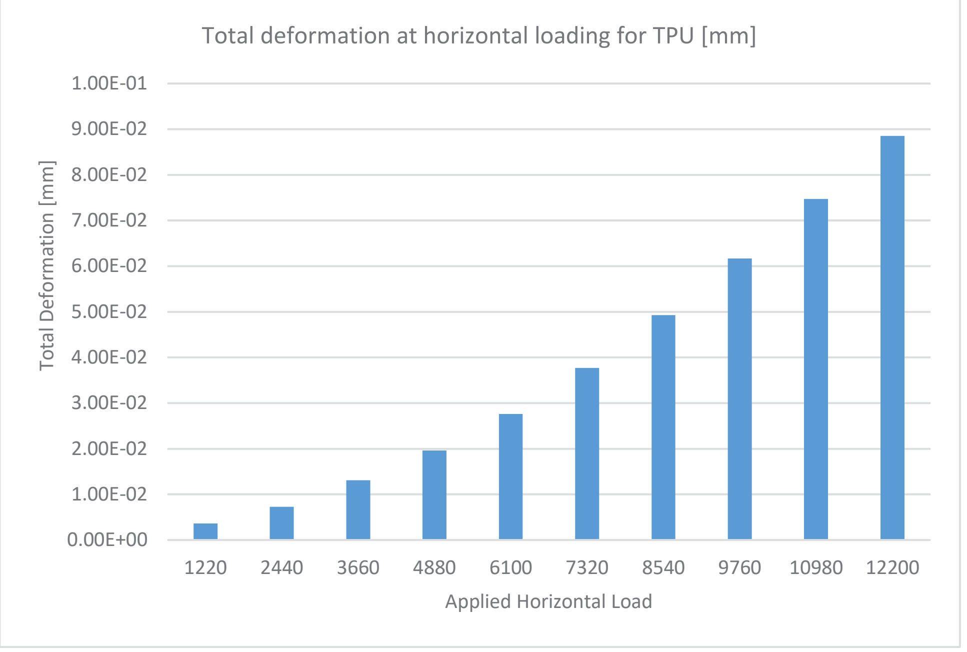

Fig. 3: Total deformation at horizontal loading

According to the graph in Fig. 3, Thermoplastic Polyurethane (TPU) will deform by a certain amount when a compressive horizontal load is applied. A linear deformation curve shows that the TPU experiences an increase in deformation as the horizontal load increases from 1220 units to 12200 units, starting at a value of 3.63E-03 mm and gradually increasing to 8.85E-02 mm. According to this linear trend, TPU deforms more as more compressive force is applied horizontally, indicating that it responds consistently to the testing conditions mechanically.

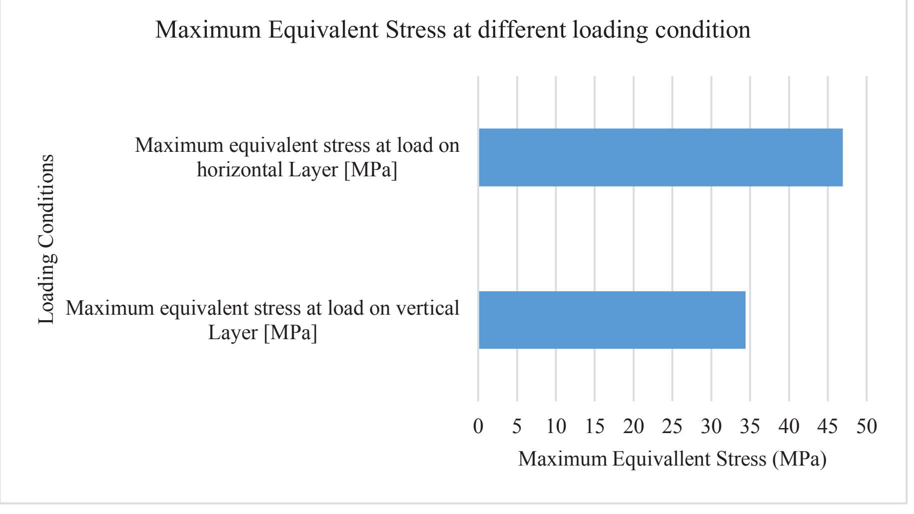

Fig. 4: Maximum Equivalent Stress at different loading condition

In the graph provided in Fig. 4, Thermoplastic Polyurethane (TPU) is shown to experience maximum equivalent stress under two loading conditions. TPU's maximum equivalent stress

(MPa) is 34.406 megapascals (MPa) when it is subjected to a load. The maximum equivalent stress of 46.933 MPa is observed for a horizontal layer, while 46.920 MPa is observed for a vertical layer. TPU responds to stress more strongly when loads are horizontal than vertical, which may be due to its anisotropic mechanical properties or to the loading direction.

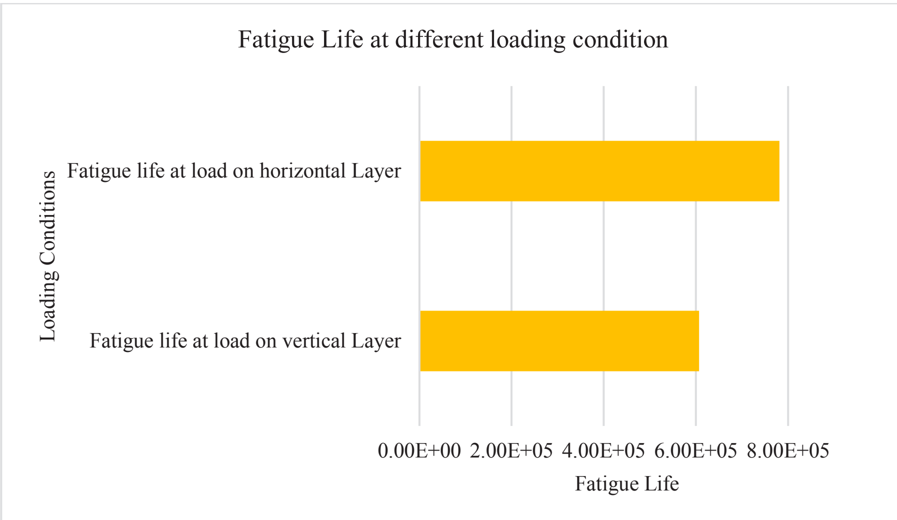

Fig. 5: Fatigue Life at different loading condition

The fatigue life of a material is measured by how many cycles it can withstand before failure. According to Fig. 5, a vertical layer exhibiting a load exhibits a fatigue life of 6.07E+05 cycles. As a result, TPU can endure more load cycles than vertical TPU when the load is horizontal, as its fatigue life increases to 7.81E+05 cycles when the load is horizontal.

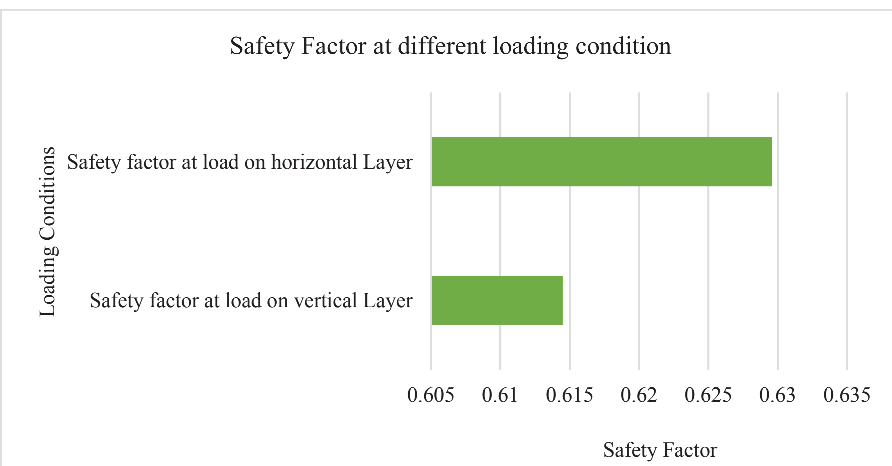

Fig. 6: Fatigue Life at different loading condition

Safety factors indicate the maximum load a material can tolerate in its application compared to the load at which it will fail. According to Fig. 6 TPU's safety factor, when applied to a vertical layer, the actual strength is just over half of what is needed to prevent failure. For a load on a horizontal layer, the safety factor increases slightly to 0.6296, suggesting that the material is marginally more capable of bearing the load without failing.

5 Conclusion

Using finite element analysis (FEA), this study explores the durability and structural properties of 3D-printed thermoplastic polyurethane (TPU) square blocks. Various testing conditions were applied to a simple structure with dimensions of 25 mm x 25 mm x 25 mm, including static structural analysis, fatigue analysis, and modal analysis. Following a comprehensive compression test structural analysis conducted on a square block composed of TPU material subjected to a vertical load of 12,200 N, several key findings have been unveiled.

- Total deformation of the block was 0.0884 mm.
- Equivalent stress distribution within the block ranged from 34.406 MPa at the outer layer to 23.338 MPa at the middle layer. Equivalent stress distribution ranged from 46.933 MPa at the bottom layer to 20.196 MPa at the top layer.
- Analysis revealed a minimum fatigue life of 6.065E+5 cycles before potential failure, primarily at the corner of the structure. Fatigue life estimated at 7.8125E+5 cycles, with the most vulnerable point at the corner
- Structural safety considerations revealed a minimum safety factor of 0.6145 for fatigue failure at a designated design life.

References

1. Ryspayeva, Assel, Thomas David Arthur Jones, Sadeque Reza Khan, MohammadrezaNekouieEsfahani, Matthew P. Shuttleworth, Russell A. Harris, Robert W. Kay, Marc PY Desmulliez, and Jose Marques-Hueso. "Selective metallization of 3D printable thermoplastic polyurethanes." IEEE Access 7 (2019): 104947-104955.
2. Yuan, Yifan, and Cynthia Sung. "Programmable Stiffness and Applications of 3D Printed TPU Grid Lattices." In International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, vol. 85444, p. V08AT08A016. American Society of Mechanical Engineers, 2021.
3. Wang, Jun, Bin Yang, Xiang Lin, Lei Gao, Tao Liu, Yonglai Lu, and Runguo Wang. "Research of TPU materials for 3D printing aiming at non-pneumatic tires by FDM method." Polymers 12, 11 (2020): 2492.
4. Lopes, Lucas, Luca Penazzato, Daniel C. Reis, Manuela Almeida, Daniel V. Oliveira, and Paulo B. Lourenço. "A Holistic Modular Solution for Energy and Seismic Renovation of Buildings Based on 3D-Printed Thermoplastic Materials." Sustainability 16, 5 (2024): 2166.
5. Yang, Leipeng, Xin Liu, Yuan Xiao, Yongyan Zhang, Gaiping Zhang, and Yuping Wang. "3D Printing of Carbon Nanotube (CNT)/Thermoplastic Polyurethane (TPU) Functional Composites and Preparation of Highly Sensitive, Wide-range Detectable, and Flexible Capacitive Sensor Dielectric Layers via Fused Deposition Modeling (FDM)." Advanced Materials Technologies 8, 7 (2023): 2201638.
6. Romero-Ramirez, Edwar, Charisma Clarke, Sanna F. Siddiqui, and Gerardo Carbajal. "Mechanical Properties and Durometer Testing Relationship of Thermoplastic Polyurethane." In ASME International Mechanical Engineering Congress and Exposition, 85697, V013T15A003. American Society of Mechanical Engineers, 2021.
7. Abbot, D. W., D. V. V. Kallon, C. Anghel, and P. Dube. "Finite element analysis of 3D printed model via compression tests." Procedia Manufacturing 35 (2019): 164-173.
8. Reppel, Thomasa, and Kerstin Weinberg. "Experimental determination of elastic and rupture properties of printed Ninjaflex." TechnischeMechanik-European Journal of Engineering Mechanics 38, 1 (2018): 104-112.

9. Huber, Justin, Stacey Slone, and Babak Bazrgari. "An evaluation of 3D printable elastics for post stroke dynamic hand bracing: a pilot study." Assistive Technology 35, 6 (2023): 513-522.
10. Dhangar, Manish, Kamna Chaturvedi, MedhaMili, Shiv Singh Patel, Mohammed Akram Khan, Hari Narayan Bhargaw, Avanish Kumar Srivastava, and Sarika Verma. "Emerging 3D printed thermal insulating materials for sustainable approach: A review and a way forward." Polymers for Advanced Technologies 34, 5 (2023): 1425-1434.
11. Jayabal, Ravikumar, Sekar Subramani, Damodharan Dillikannan, Yuvarajan Devarajan, Lakshmanan Thangavelu, Mukilarasan Nedunchezhiyan, Gopal Kaliyaperumal, and Melvin Victor De Poures. "Multi-objective optimization of performance and emission characteristics of a CRDI diesel engine fueled with sapota methyl ester/diesel blends." Energy 250 (2022): 123709.
12. Swarna, K. S. V., Arangarajan Vinayagam, M. Belsam Jeba Ananth, P. Venkatesh Kumar, Veerapandiyan Veerasamy, and Padmavathi Radhakrishnan. "A KNN based random subspace ensemble classifier for detection and discrimination of high impedance fault in PV integrated power network." Measurement 187 (2022): 110333.
13. Sridhara, V., B. S. Gowrishankar, Snehalatha, and L. N. Satapathy. "Nanofluids—a new promising fluid for cooling." Transactions of the Indian Ceramic Society 68, no. 1 (2009): 1-17.
14. Alkorbi, Ali S., K. Yogesh Kumar, M. K. Prashanth, L. Parashuram, Antonio Abate, Fahad A. Alharti, Byong-Hun Jeon, and M. S. Raghu. "Samarium vanadate affixed sulfur self doped g-C3N4 heterojunction; photocatalytic, photoelectrocatalytic hydrogen evolution and dye degradation." International Journal of Hydrogen Energy 47, 26 (2022): 12988-13003.
15. Kumar, CB Pradeep, M. S. Raghu, B. S. Prathibha, M. K. Prashanth, G. Kanthimathi, K. Yogesh Kumar, L. Parashuram, and Fahad A. Alharthi. "Discovery of a novel series of substituted quinolines acting as anticancer agents and selective EGFR blocker: Molecular docking study." Bioorganic & Medicinal Chemistry Letters 44 (2021): 128118.
16. Manohar, T., S. C. Prashantha, H. P. Nagaswarupa, Ramachandra Naik, H. Nagabhushana, K. S. Anantharaju, KR Vishnu Mahesh, and H. B. Premkumar. "White light emitting lanthanum aluminate nanophosphor: near ultra violet excited photoluminescence and photometric characteristics." Journal of Luminescence 190 (2017): 279-288.
17. Srinivasan, K., K. Porkumaran, and G. Sainarayanan. "Improved background subtraction techniques for security in video applications." In 2009 3rd International Conference on Anti-counterfeiting, Security, and Identification in Communication, pp. 114-117. IEEE, 2009.
18. Ram, J. Prasanth, Dhanup S. Pillai, Amer MYM Ghias, and N. Rajasekar. "Performance enhancement of solar PV systems applying P&O assisted Flower Pollination Algorithm (FPA)." Solar Energy 199 (2020): 214-229.
19. Yogananda, H. S., R. B. Basavaraj, G. P. Darshan, B. Daruka Prasad, Ramachandra Naik, S. C. Sharma, and H. Nagabhushana. "New design of highly sensitive and selective MoO3: Eu3+ micro-rods: Probing of latent fingerprints visualization and anti-counterfeiting applications." Journal of colloid and interface science 528 (2018): 443-456.
20. Prakash, Shanmugam, Govindharaj Somiya, Nagaraj Elavarasan, Kasivisvanathan Subashini, Selvaraj Kanaga, Ramamurthy Dhandapani, Magudeeswaran Sivanandam, Poomani Kumaradhas, Chinnasamy Thirunavukkarasu, and Venugopal Sujatha. "Synthesis and characterization of novel bioactive azo compounds fused with

benzothiazole and their versatile biological applications." Journal of Molecular Structure 1224 (2021): 129016.
21. SudhirSastry, Y. B., Pattabhi R. Budarapu, N. Madhavi, and Y. Krishna. "Buckling analysis of thin wall stiffened composite panels." Computational Materials Science 96 (2015): 459-471.
22. Sastry, YB Sudhir, Pattabhi R. Budarapu, Y. Krishna, and S. Devaraj. "Studies on ballistic impact of the composite panels." Theoretical and Applied Fracture Mechanics 72 (2014): 2-12.
23. Jayanthi, Neelampalli, B. Vijaya Babu, and N. Sambasiva Rao. "Survey on clinical prediction models for diabetes prediction." Journal of Big Data 4 (2017): 1-15.
24. Ramu, Gandikota. "A secure cloud framework to share EHRs using modified CP-ABE and the attribute bloom filter." Education and Information Technologies 23, no. 5 (2018): 2213-2233.
25. Lakshmi, L., M. Purushotham Reddy, Chukka Santhaiah, and U. Janardhan Reddy. "Smart phishing detection in web pages using supervised deep learning classification and optimization technique ADAM." Wireless Personal Communications 118, no. 4 (2021): 3549-3564.
26. Cheruvu, Aravind, V. Radhakrishna, and N. Rajasekhar. "Using normal distribution to retrieve temporal associations by Euclidean distance." In 2017 International Conference on Engineering & MIS (ICEMIS), pp. 1-3. IEEE, 2017.
27. Vallabhuni, Rajeev Ratna, S. Lakshmanachari, G. Avanthi, and Vallabhuni Vijay. "Smart cart shopping system with an RFID interface for human assistance." In 2020 3rd International Conference on Intelligent Sustainable Systems (ICISS), pp. 165-169. IEEE, 2020.
28. Kumar, K. Udaya, P. Babu, Ch Basavapoornima, R. Praveena, D. Shobha Rani, and C. K. Jayasankar. "Spectroscopic properties of Nd3+-doped boro-bismuth glasses for laser applications." Physica B: Condensed Matter 646 (2022): 414327.
29. Rani, Bandi Mary Sowbhagya, Vasumathi Devi Majety, Chandra Shaker Pittala, Vallabhuni Vijay, Kanumalli Satya Sandeep, and Siripuri Kiran. "Road Identification Through Efficient Edge Segmentation Based on Morphological Operations." Traitement du Signal 38, no. 5 (2021).
30. Radhakrishna, Vangipuram, P. V. Kumar, V. Janaki, and N. Rajasekhar. "Estimating prevalence bounds of temporal association patterns to discover temporally similar patterns." In International Conference on Soft Computing-MENDEL, pp. 209-220. Cham: Springer International Publishing, 2016.
31. Bates, Simon RG, Ian R. Farrow, and Richard S. Trask. "Compressive behaviour of 3D printed thermoplastic polyurethane honeycombs with graded densities." Materials & Design 162 (2019): 130-142.
32. Ge, Changfeng, Lakshmi Priyadarshini, Denis Cormier, Liao Pan, and Jonathan Tuber. "A preliminary study of cushion properties of a 3D printed thermoplastic polyurethane Kelvin foam." Packaging Technology and Science 31, no. 5 (2018): 361-368.
33. Gul, Jahan Zeb, Memoon Sajid, and Kyung Hyun Choi. "Retracted Article: 3D printed highly flexible strain sensor based on TPU–graphene composite for feedback from high speed robotic applications." Journal of Materials Chemistry C 7, no. 16 (2019): 4692-4701.
34. Wang, Jun, Bin Yang, Xiang Lin, Lei Gao, Tao Liu, Yonglai Lu, and Runguo Wang. "Research of TPU materials for 3D printing aiming at non-pneumatic tires by FDM method." Polymers 12, no. 11 (2020): 2492.
35. Brancewicz-Steinmetz, Emila, Jacek Sawicki, and Paulina Byczkowska. "The influence of 3D printing parameters on adhesion between polylactic acid (PLA) and thermoplastic polyurethane (TPU)." Materials 14, no. 21 (2021): 6464.