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MITIGATING SPATIAL-INTERPRETATION BARRIERS IN MECHANICS OF MATERIALS THROUGH BROWSER-BASED 3D MODELS AND ADDITIVELY MANUFACTURED REPLICAS: A QUALITATIVE STUDY

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Resumo:

Mechanics of Materials is a core subject in mechanical engineering curricula, yet many students struggle not only with analytical procedures, but also with the prior step of correctly interpreting the geometrical, loading, and support conditions represented in exercise statements. This paper reports the qualitative stage of a broader educational investigation conducted with more than 100 undergraduate students enrolled in a Mechanics of Materials course. The study focused on recurrent difficulties associated with the interpretation of technical drawings, schematic representations, and illustrative figures provided in problem statements. The diagnostic stage combined two complementary sources of evidence: the identification of exercises with a high incidence of solution errors and follow-up student interviews indicating that misinterpretation of the statement, rather than purely mathematical weakness, was a major cause of failure. Based on these findings, two complementary instructional strategies were implemented. First, three-dimensional models of selected exercises were created and made available online through GrabCAD, allowing students to inspect the geometries without requiring local CAD installation. Second, additively manufactured physical models of the exercises to be discussed in class were used during problem-solving sessions to support visualization and interpretation. The paper discusses the pedagogical rationale of this dual intervention and illustrates its application through a representative exercise drawn from a globally adopted reference textbook. By integrating digital and physical visualization resources into the teaching of Mechanics of Materials, the study proposes a low-cost and replicable approach to support spatial reasoning and improve the interpretation of engineering problem statements. Quantitative assessment of failure modes and of the effectiveness of the implemented actions is currently being consolidated and will be reported in a subsequent study.

Palavras-chave: Mechanics of Materials, Engineering Education, Spatial Visualization, Additive Manufacturing, Problem Statement Interpretation

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1 INTRODUCTION

Mechanics of Materials occupies a pivotal position in mechanical engineering curricula because it connects mathematical formalism to the interpretation of stress, strain, equilibrium, deformation, and structural response in real components and systems (PORAT; CEOBANU, 2024a). Yet the cognitive demands of engineering learning are not limited to symbolic manipulation, since students must also build coherent internal representations of geometry, loading, support conditions, and three-dimensional relationships before a correct analytical procedure can even begin (OJE *et al.*, 2023).

In visually intensive domains, difficulties frequently emerge when learners are required to translate between different semiotic registers, such as verbal descriptions, schematic diagrams, orthographic views, and mathematical expressions, and these representational discontinuities may hinder meaningful problem solving even when procedural knowledge is partially available (OVODENKO; KOUROPATOV, 2025).

Recent research in engineering drawing has shown that students' errors are often rooted not only in insufficient technical knowledge, but also in difficulties in interpreting graphical information and in structuring an appropriate visual reading of the problem itself (KADAM *et al.*, 2024). This challenge is closely related to spatial ability, which has long been recognised as an essential competence in engineering education because it supports the generation, retention, manipulation, and transformation of abstract visual information during technical reasoning (PORAT; CEOBANU, 2024b).

The relevance of this issue is further reinforced by recent evidence showing that descriptive-geometry instruction becomes more effective when students are supported by approaches that reduce unnecessary procedural burden while strengthening spatial comprehension and graphical accuracy (RAVÉ *et al.*, 2025).

For this reason, a growing body of literature has explored visualization-oriented interventions in engineering education, including augmented reality, virtual reality, CAD-based environments, and other interactive three-dimensional learning resources (TIWARI *et al.*, 2024). Such interest is pedagogically justified, since a recent meta-analysis on visualization interventions reported positive and lasting effects on learning, thereby reinforcing the educational value of external visual supports in conceptually demanding subjects (SCHOENHERR *et al.*, 2024). At the same time, immersive and interactive environments have been shown to improve the comprehension of complex three-dimensional structures more effectively than conventional two-dimensional digital resources in selected engineering-learning contexts (KA *et al.*, 2025).

Physical artefacts also remain highly relevant in technically abstract subjects, since hands-on models can support the transition from theoretical description to embodied understanding and foster a more concrete engagement with disciplinary concepts (SEKARAN; RODAK, 2024). In parallel, recent work on the integration of digital and physical learning environments suggests that the combination of virtual resources with tangible systems may produce more robust educational experiences than reliance on either modality alone (ZHANG *et al.*, 2025).

This perspective is consistent with current discussions on 3D printing in engineering education, which emphasise its potential to materialise abstract forms, promote active engagement, and support the interpretation of component geometry and functionality through accessible physical replicas (MUNIR *et al.*, 2024).

Within this context, the present paper reports the qualitative stage of a broader educational study carried out in a Mechanics of Materials course with a cohort of more than one hundred undergraduate students, focusing specifically on the recurrent difficulty of correctly interpreting the technical drawings, illustrative schemes, and graphical statements associated with problem-solving activities.

The study was structured around two complementary instructional responses to that difficulty: the online availability of selected exercise models through a browser-accessible 3D repository and the classroom use of additively manufactured replicas corresponding to the exercises discussed in problem-solving sessions.

Rather than presenting quantitative effectiveness data, which are still being consolidated for a subsequent publication, this paper aims to discuss the qualitative diagnosis that motivated the intervention and to describe the pedagogical rationale underlying the combined use of digital and physical visualization resources in Mechanics of Materials.

2 LITERATURE REVIEW

A recurring theme in recent engineering-education research is that success in mechanics problem solving depends on more than procedural fluency, since students must coordinate verbal, graphical, symbolic, and conceptual representations in a coherent manner. Niyomufasha *et al.* (2024) showed that engineering students' use of multiple representations remains uneven and that difficulties in moving effectively between such representations continue to constrain performance, thereby reinforcing the pedagogical relevance of interventions specifically aimed at representational interpretation.

This issue becomes even more critical when the instructional material relies on technical drawings or schematic depictions whose meaning is not immediately transparent to novice learners. Company *et al.* (2024) recently argued that the interpretation of technical drawings is an essential engineering skill that may require the explicit resolution of ambiguity, and their proposed classification of drawing-related ambiguities, including omission, contradiction, redundancy, and polysemy, highlights that graphical misunderstanding is not a superficial mistake, but rather a structurally relevant source of error in the transition from two-dimensional documentation to three-dimensional understanding.

In response to these limitations, recent studies have increasingly explored digital three-dimensional environments capable of making technical content more accessible without imposing the burden of specialised software or complex local installation. Weis *et al.* (2025), for instance, reported that static two-dimensional schematics are often insufficient to convey complex spatial relations in engineering education and proposed a web-based digital-twin framework that operates directly in the browser, with qualitative and quantitative evidence indicating gains in usability, spatial understanding, and technical knowledge transfer. This line of work is particularly relevant to educational contexts in which scalable access and low entry barriers are pedagogically decisive.

Another important strand of the literature concerns the use of immersive and interactive visualisation systems to connect external representation with structural behaviour. Mojidra *et al.* (2025) developed a mobile augmented-reality application for structural analysis that overlays real-time feedback onto physical models, enabling students to visualise deflections, reactions, shear forces, and bending moments under applied loads. Their findings suggest that such an approach supports a more tangible interpretation of structural response and helps mitigate the limitations associated with traditional two-dimensional representations, especially in conceptually demanding topics where spatial reasoning and behavioural interpretation must occur simultaneously.

Alongside digital environments, additive manufacturing has also been increasingly recognised as an educational resource capable of strengthening experiential learning in engineering. A recent framework proposed by To *et al.* (2024) emphasises that additive manufacturing and 3D printing create distinctive opportunities for practical application and hands-on engagement in engineering education, precisely because they allow learners to move from abstract description to manufacturable artefact.

From a pedagogical standpoint, this is especially valuable in subjects where the comprehension of geometry, topology, and load-bearing configuration depends on the learner's ability to mentally reconstruct the object that the statement only partially describes.

More specifically in graphical and design-oriented instruction, recent evidence indicates that the educational value of physical realisation extends beyond motivation and engagement. Trajkovski *et al.* (2025), in a study on technical drawing, reported that integrating collaborative project work with hands-on manufacturing experience improved learning outcomes, student satisfaction, and peer interaction, suggesting that the act of materialising geometry may deepen comprehension of representational content rather than merely supplement it.

Against this background, the present study adopts a narrower and more discipline-specific perspective by examining how the combined use of browser-accessible 3D models and additively manufactured replicas can address a particular instructional bottleneck in Mechanics of Materials, namely the incorrect interpretation of exercise statements and their associated graphical representations.

3 METHODOLOGY

3.1 Research design

This paper reports the qualitative stage of a broader educational investigation conducted in a Mechanics of Materials course offered within two Mechanical Engineering programmes. The broader study was conceived to identify recurrent learning difficulties, examine their possible causes, and support the design of pedagogical actions aimed at improving students' comprehension of core disciplinary concepts and problem-solving procedures. The present manuscript is intentionally restricted to the qualitative component of that investigation and, therefore, does not include the numerical consolidation of failure modes or the quantitative assessment of the effectiveness of the implemented actions.

The methodological orientation adopted in this stage was qualitative and interpretative. Its purpose was not to measure performance gains statistically, but rather to understand a recurring instructional difficulty reported by both instructors and students, namely the inadequate interpretation of technical drawings, illustrative schemes, and graphical information embedded in exercise statements. In this sense, the study focused on the diagnostic reconstruction of the problem and on the pedagogical rationale that guided the subsequent intervention.

3.2 Educational context and participants

The study was carried out over the previous academic year with a cohort of more than one hundred undergraduate students enrolled in Mechanics of Materials. The course is part of the Mechanical Engineering curriculum and requires students to interpret geometrical configurations, loading conditions, support arrangements, and section properties before performing the analytical development of each problem. Because of this intrinsic dependence on graphical and spatial interpretation, the course offers a particularly suitable context for investigating the role of visual comprehension in students' errors.

In addition to the students' participation, the study was informed by the combined teaching experience of two instructors responsible for the discipline. Their long-term contact

with recurring student difficulties contributed to the initial identification of the problem and to the organisation of the qualitative analysis. The instructional perspective adopted in the study was therefore grounded in both classroom observation and subsequent student feedback.

3.3 Diagnostic stage and selection of representative exercises

The diagnostic stage began with the identification of exercises that had exhibited a high incidence of incorrect student solutions. Rather than treating all incorrect answers as equivalent, the analysis sought to distinguish situations in which the main obstacle seemed to arise before the formal analytical procedure itself. Particular attention was therefore directed to exercises in which the solution error appeared to be associated with an inadequate understanding of the problem statement, especially of the accompanying drawing or schematic representation.

To refine this interpretation, the selected exercises were revisited in light of follow-up student interviews conducted after the corresponding problem-solving activities. In those interviews, students were invited to comment on the origin of their errors and on the aspects of the exercise they had found most difficult to understand. A recurring pattern emerged from these reports, namely that a significant portion of the difficulty was attributed not to the mathematical treatment alone, but to an incorrect reading of the figure, the geometry, or the physical arrangement represented in the statement. This convergence between error concentration and student testimony was used as the main qualitative criterion for selecting the exercises to be addressed by the intervention.

3.4 Pedagogical intervention design

Once the representational difficulty had been identified, two complementary instructional strategies were defined. The first strategy consisted of producing three-dimensional digital models of selected exercises and making them available online through GrabCAD. The decision to use this platform was pedagogically motivated by its accessibility, since it allows students to inspect the models without the need for local installation of CAD software. This feature was considered especially relevant for enabling broader and more immediate access to the visual material outside the classroom.

The second strategy consisted of producing physical replicas of the selected exercise models by means of additive manufacturing and bringing these artefacts to the corresponding problem-solving classes. The intention was to allow students to inspect, manipulate, and discuss the geometry of the exercise before or during the analytical development carried out in class. By materialising the object represented in the statement, the intervention aimed to reduce ambiguity in spatial interpretation and to strengthen the connection between the two-dimensional enunciation and the three-dimensional physical configuration it was intended to describe.

These two strategies were conceived as complementary rather than alternative. The digital model offered flexible access and autonomous exploration, whereas the printed model provided immediate physical reference during classroom interaction. Together, they formed a combined visualisation approach designed to support students in the preliminary interpretative stage of problem solving.

3.5 Model development and classroom use

After the selection of the representative exercises, three-dimensional models corresponding to their geometrical configurations were developed. These models were created with the specific purpose of preserving the essential physical and geometrical features required for the correct interpretation of the exercise statement.

The focus was not on producing highly detailed engineering models, but on constructing pedagogically meaningful representations capable of clarifying the spatial arrangement that students had previously misunderstood.

The digital versions were uploaded to GrabCAD and made available for student access. In parallel, selected models were fabricated by additive manufacturing and used during exercise classes in which the corresponding problems were discussed. During these sessions, the printed models functioned as concrete visual supports that accompanied the explanation of the statement and the subsequent analytical procedure.

The aim was to make explicit the relation between geometry, loading, supports, and the mechanical reasoning required for the solution.

3.6 Illustrative case

To illustrate the application of the proposed approach, the paper presents one representative exercise taken from one of the reference textbooks adopted in the course. The choice of this case was based on its pedagogical relevance and on its alignment with the type of difficulty identified in the diagnostic stage.

More specifically, the exercise exemplifies a situation in which incorrect interpretation of the graphical representation may compromise the entire analytical path, even when the required theoretical content is formally known by the student.

The selected case is not intended to exhaust the range of difficulties identified throughout the broader study. Instead, it serves as an analytically meaningful example through which the diagnostic logic and the instructional response can be clearly discussed. In this respect, the case functions as a representative illustration of the methodological procedure adopted in the qualitative phase.

3.7 Scope and limitations of the present paper

The methodological scope of this paper is deliberately limited to the qualitative dimension of the investigation. Its purpose is to document the identification of a recurrent representational difficulty in Mechanics of Materials and to describe the reasoning that led to the implementation of a dual visualisation strategy based on browser-accessible three-dimensional models and additively manufactured classroom artefacts.

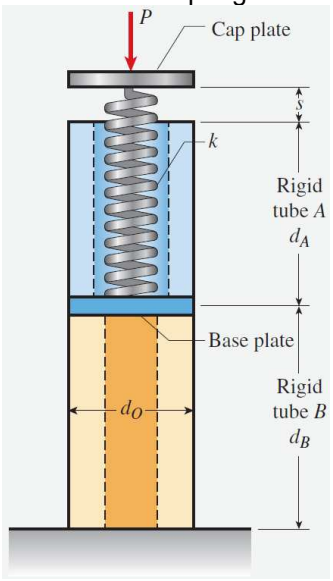
Accordingly, this paper does not present numerical comparisons of error rates, formal categorisation of all failure modes, or quantified evidence of intervention effectiveness. These elements belong to the broader study and are currently being consolidated for subsequent publication.

The contribution of the present manuscript lies instead in making explicit the educational diagnosis, the intervention logic, and the methodological path through which a specific learning difficulty was transformed into a targeted pedagogical action.

4 RESULTS

To illustrate the nature of the interpretative difficulty identified in the course, a representative case study was selected from the reference textbook adopted in Mechanics of Materials, namely Example 1-5 from Goodno and Gere (2021), presented in Figure 1.

Figure 1 – Exercise that considers an elastic spring inside rigid tubes being compressed.



Source: Goodno and Gere (2021)

The exercise describes an axial loading system composed of an elastic spring, a base plate, a cap plate, and two rigid tubes with distinct geometric characteristics. The problem requires the determination of the normal stresses in tubes A and B under different loading conditions, taking into account the stiffness of the spring, the geometric dimensions of the components, and the initial dimensional offset between the spring and one of the tubes.

From a purely analytical perspective, the exercise may appear straightforward, since the statement provides all the numerical parameters required for the mechanical treatment. However, its actual difficulty lies at a more fundamental level. Before any equilibrium relation or constitutive expression can be applied, the student must correctly interpret the physical arrangement of the assembly and understand how the load is transmitted through the system. In other words, the problem cannot be solved adequately unless the learner first reconstructs, in a coherent mechanical sense, the role played by each component in the overall configuration. This aspect makes the exercise especially relevant for a qualitative educational analysis.

The statement involves more than the recognition of isolated dimensions or material parameters. It demands an accurate interpretation of the relative positions of the spring and the tubes, the function of the enclosing tube, the interaction between the cap plate and the structural members, and the significance of the initial gap represented by the dimensional parameters. If this spatial and functional reading is not correctly established, the student may formulate an incorrect load path from the outset, which compromises the entire solution procedure regardless of the correctness of the subsequent calculations. A particularly important feature of this example is that the system does not behave as a conventional set of axially loaded members subjected simultaneously and uniformly to the same force. Instead, the mechanical response depends on the sequence of engagement among the components. The spring initially undergoes compression, while the structural participation of the tubes depends on the geometric compatibility of the assembly and on the progressive evolution of deformation.

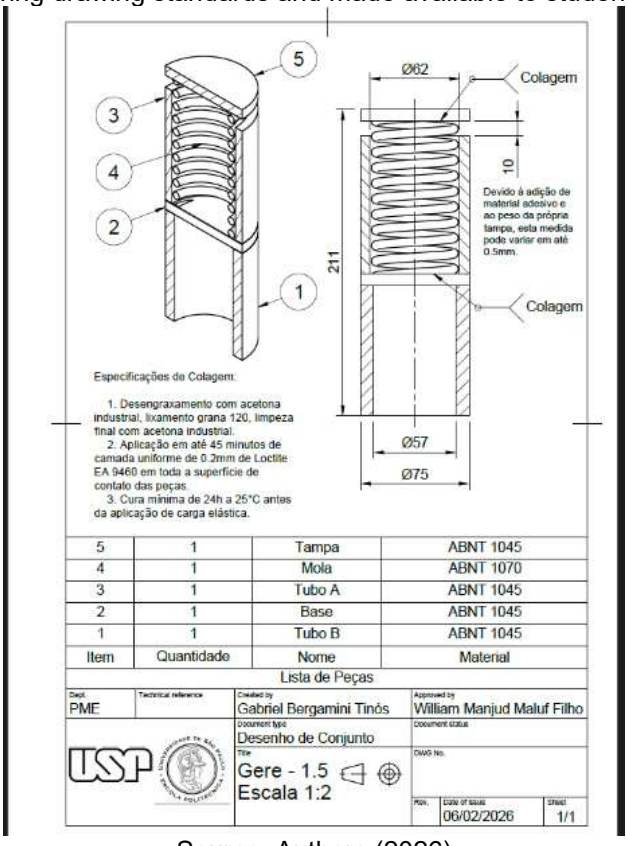
Therefore, the exercise requires the student to reason not only in terms of force and stress, but also in terms of contact, compatibility, and staged activation of load-carrying elements. This interpretative demand explains why the selected example proved pedagogically significant within the broader study. In classroom practice, incorrect student responses to this type of problem were often not attributable solely to deficiencies in algebraic manipulation or

to misunderstandings of the stress formula itself. Rather, a substantial portion of the difficulty emerged at the moment of reading the figure and assigning a correct physical meaning to the configuration shown in the statement. The error, therefore, was frequently conceptual and representational before it became mathematical. For this reason, the exercise was considered particularly suitable as a qualitative case through which the rationale of the proposed intervention could be discussed. Its structure makes visible the close relationship between graphical interpretation and mechanical reasoning in Mechanics of Materials.

The case demonstrates that, in certain problems, student failure may originate in an incomplete or distorted mental reconstruction of the geometry and of the interaction between the elements, which in turn affects the identification of the resisting members, the understanding of the loading sequence, and the correct formulation of the governing equations. In the context of the present study, the selected example served as a pedagogically meaningful instance of the broader difficulty diagnosed throughout the course. It provided an appropriate basis for examining how external visualization supports, both digital and physical, could help students move from a two-dimensional statement to a more accurate three-dimensional and mechanically consistent interpretation of the problem. Accordingly, the case was not chosen because of computational complexity, but because it clearly exposed the representational bottleneck that motivated the instructional actions described in this paper.

In order to support students' interpretation of the selected exercise, a technical assembly drawing of the system was developed in accordance with standard engineering drawing conventions, including dimensional definition, sectional representation, item identification, and bill of materials. The drawing, presented in Figure 2, was not conceived merely as an illustration, but as a pedagogically structured representation intended to make the spatial arrangement and the functional relationship among the components more explicit.

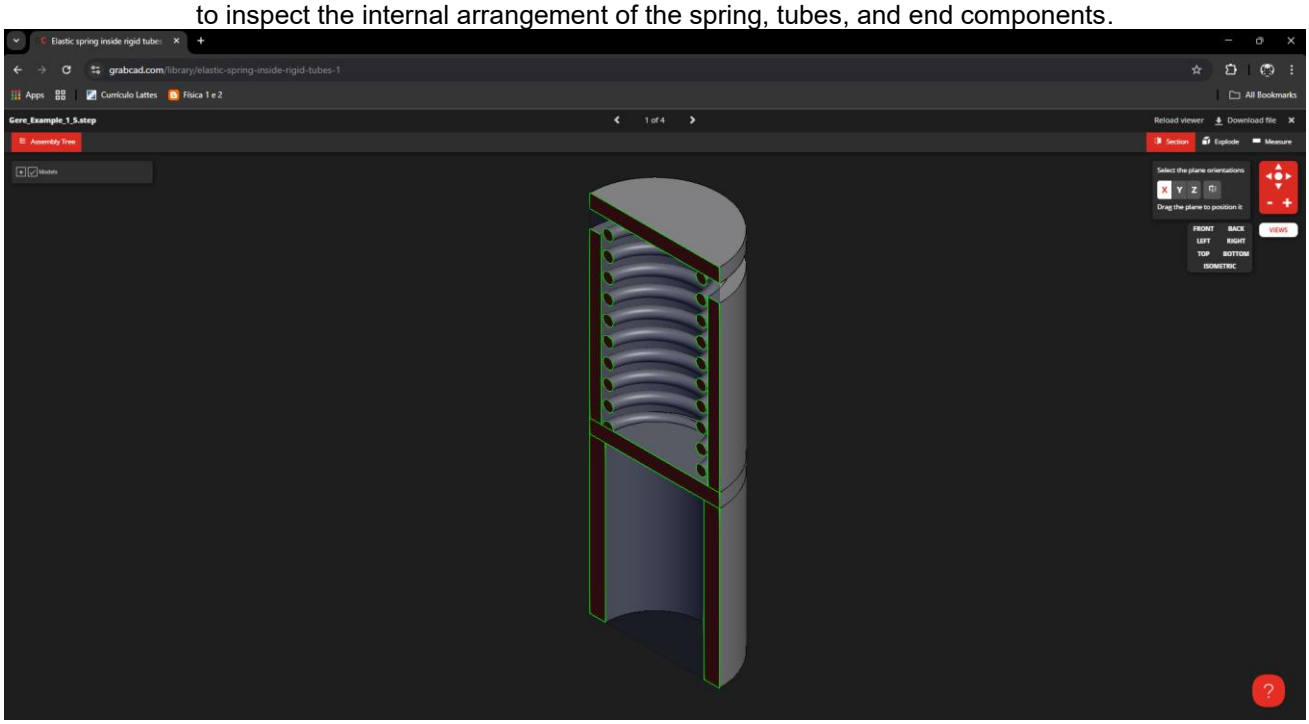
Figure 2 – Technical assembly drawing of the Goodno and Gere (2021) Example 1-5 system, prepared according to engineering drawing standards and made available to students through GrabCAD.



Source: Authors (2026)

To extend access beyond the classroom and allow autonomous inspection by the students, the corresponding digital model and associated drawing were made available online through GrabCAD. The 3D model is presented in Figure 3.

Figure 3 – Sectioned 3D model of the selected exercise made available on GrabCAD, allowing students to inspect the internal arrangement of the spring, tubes, and end components.



Source: https://grabcad.com/library/elastic-spring-inside-rigid-tubes-1.

After the pedagogical 3D model had been defined, the assembly was adapted for additive manufacturing in order to produce the physical artefact used during the exercise class. For this purpose, the system was reorganized into printable components, preserving the essential geometric and functional relationships of the original problem while making fabrication and subsequent assembly feasible. The exploded 3D model is shown in Figure 4.

Figure 4 – Exploded 3D model of the selected exercise, prepared for additive manufacturing and subsequent assembly as a physical teaching aid.



Source: Authors (2026)

This step was not intended to reproduce the exercise as a manufacturing project, but rather to create a tangible instructional model capable of helping students visualize the relative position and interaction of the spring, tubes, base, and cap. The printed set therefore functioned as a classroom support resource, complementing the digital model previously made available online.

After the model had been prepared for additive manufacturing, the complete printed assembly was produced and taken to the exercise class as a physical teaching aid. Figure 5 shows the assembled printed model, which reproduced the general external configuration of

the system discussed in the selected textbook problem. In this form, the artefact allowed students to perceive the overall proportions of the assembly and to relate the abstract statement to a tangible object.

Figure 5 – Fully assembled 3D-printed model of the exercise used in the classroom as a physical teaching aid.



Source: Authors (2026)

In order to make the internal arrangement more explicit, additional portions of the printed model were deliberately removed. Figure 6 shows the partially open configuration, which allowed students to visualize the relative position of tube A, tube B, the spring, and the end components more directly.

Figure 6 – Partially opened 3D-printed model showing the internal arrangement of tube A, tube B, the spring, and the end components to facilitate students' visualization of the system.



Source: Authors (2026)

This open view was particularly useful for clarifying how the spring is positioned within the assembly and how the structural elements interact during loading. As a result, the model supported a more immediate interpretation of the mechanical configuration represented in the original figure and helped reduce ambiguity during classroom discussion.

5 CONCLUSIONS

This paper addressed a recurrent learning difficulty observed in Mechanics of Materials, namely the inadequate interpretation of technical drawings, illustrative schemes, and graphical representations embedded in exercise statements. Rather than treating students' errors exclusively as consequences of insufficient analytical ability, the present study adopted a qualitative perspective and highlighted that, in several cases, failure originated at an earlier stage of the problem-solving process, when the geometrical and physical meaning of the statement had not yet been properly understood.

From this diagnostic standpoint, the study proposed and described a dual instructional response based on two complementary visualization resources. The first consisted of making selected exercise models available online through a browser-accessible three-dimensional repository. The second involved the use of additively manufactured physical replicas during problem-solving classes. Together, these resources were conceived as pedagogical supports intended to reduce ambiguity, strengthen spatial comprehension, and facilitate the transition from two-dimensional representation to three-dimensional mechanical interpretation.

The main contribution of the present paper lies in the explicit articulation between an identified instructional bottleneck and a targeted pedagogical intervention. In this sense, the study does not claim to provide a complete assessment of effectiveness, but rather to document the qualitative rationale that motivated the implementation of the adopted strategies. By doing so, it contributes to the discussion on how visualization-oriented teaching practices may support the teaching of conceptually dense engineering subjects in which graphical interpretation is inseparable from analytical reasoning.

An additional contribution of the work is its practical and replicable character. The combined use of freely accessible online models and low-cost additively manufactured artefacts constitutes an intervention that can be adapted to other topics within Mechanics of Materials and potentially extended to related disciplines in mechanical and structural engineering. The approach is particularly relevant in educational situations in which students must interpret nontrivial geometries, loading configurations, or support conditions before initiating formal calculations.

Finally, the present manuscript should be understood as the qualitative stage of a broader educational investigation. The numerical consolidation of error patterns, failure modes, and the effectiveness of the implemented actions is currently under development and will be addressed in a subsequent study. Future work will therefore be able to complement the interpretative findings reported here with quantitative evidence, thus providing a more comprehensive assessment of the educational value of integrating digital three-dimensional models and additively manufactured classroom artefacts into Mechanics of Materials instruction.

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