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INTEGRATION OF STEM TECHNOLOGIES INTO THE PROFESSIONAL TRAINING OF TRANSPORT ENGINEERS AND EXPERT EDUCATION TEACHERS

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Abstract. The article outlines a methodology for creating three-dimensional object models for a standardised approach to STEM (science, technology, engineering and mathematics) design. The study was conducted on the example of tightening the vertical levers of a freight wagon bogie. The features of the tightening design as well as the strength calculation for the rod system are described. Its loading under the action of an external force was simulated using the finite element method by means of the SolidWorks simulation software to determine the stress distribution and displacement fields in the tightening. A 3D-printing of the tightening prototype was carried out, which confirmed the accuracy of digital models and the effectiveness of additive technologies for their creation. The achieved results showed the potential for using 3D-printing to test and improve wagon brake systems. The presented methodology has practical significance for mechanical engineering, transport systems, and automation, as it can be used to reduce design and production cycles and increase the product competitiveness.

Keywords: STEM project, STEM technologies, STEM education, 3D modelling, transport mechanics, wagon braking system, transport engineers.

1. Introduction

The railway industry currently competes with other modes of transport for the passenger and cargo transportation, both domestically and internationally. Therefore, attention should be paid to the professional training of highly qualified specialists in engineering and technical specialties in the field of railway transport [1–5].

There is a growing demand for innovative approaches that will not only increase the level of knowledge of future transport engineers and vocational education teachers within the modern system of higher education, but will also provide them with practical skills to solve real problems. The STEM education (science, technology, engineering and mathematics) is becoming one of the most promising areas in education, because its goal is to develop critical thinking, creativity, and engineering proficiency among students. The introduction of STEM technologies is a response to the need of modern society to prepare future specialists for working in a high-tech environment.

One of the key elements of STEM education is the use of engineering design and modelling technologies. Thanks to these technologies, students have the opportunity to master the basics of engineering, learn to analyse and design real objects, work with 3D modelling, etc. This allows for an effective development of skills, such as the ability to solve complex problems, the ability to think creatively and logically, and the integration of knowledge in different fields.

The pedagogical definition of the concept of "project" in the educational context is characterised by multi-facetedness, where the "educational project" appears as a problem-oriented task that involves independent search and research activities of future specialists.

STEM projects play a key role in developing professional skills of future transport engineers and vocational education teachers. They ensure the integration of science, technology, engineering and mathematics in practical training. Therefore, the issue of introducing STEM methodology into the professional training of transport engineers and vocational education teachers is rather an important task.

1.1. Analysis of recent research and publications

A clear structuring and methodological substantiation of the process of implementing STEM projects is necessary to properly train and educate future specialists [6, 7]. Pedagogical research shows that the effectiveness of forming professional competencies directly depends on the systematicity and consistency of the implementation of project activities in the educational process. In this context, the phased implementation of STEM projects is of particular importance, because it ensures a logical sequence of formation of both technical and pedagogical competencies of future applicants [8].

Therefore, in the process of implementing STEM projects, it is necessary to start with design and planning. A mandatory condition for a STEM project is the research work of students, which involves their search for relevant information with subsequent processing and presentation of the results of their activities. The result of the work on a STEM project is a product created by the participants of the project group while solving the task set by the teacher. At the final stage of implementing a STEM project, a 3D model should be printed [9].

As can be seen in [10–12], 3D printing is becoming an increasingly popular method of producing components with a simple as well as complicated design together with various types of used material. 3D printing is used not only in the field of mechanical engineering, but is also used in medicine and other fields [13, 14].

A new approach to the functional classification of 3D objects, which are represented as a set of primitives, is proposed in the research [15]. Training results in the construction of a multi-level hierarchical description of objects. The division of an object into primitives is carried out by segmentation. Each class of objects corresponds to a certain hierarchy of its primitives. This allows to build a description of any functional class of objects from the studied examples automatically and to perform the division of a complex object into functional parts. However, the work does not provide an analysis of the mechanical properties for the functional parts of the object.

The work [16] is focuses on the study of the relationship between interdisciplinary systems thinking and information and communication technologies. For this purpose, information on the learning outcomes of 156 students was analysed for empirical research. Multiple regression analysis was used to process statistical information on the success of students, which made it possible to identify and evaluate the positive and negative qualities of systems thinking. It is shown that there is a need for systems thinking to solve complex problems, especially in disciplines where the design plays an important role. The systems thinking of students was assessed on a 6-point scale through a survey. A special attention was paid to the ability of students to identify cause-and-effect relationships and form the correct sequence of events.

The work [17] highlights the features of preparing applicants for mechanical engineering and architectural design. The authors pay special attention to the need for applying an interdisciplinary approach in order to teach future engineers architectural design. Thanks to this, students can effectively master the materials of elective disciplines and obtain the relevant knowledge, skills, and abilities in construction and technological and constructive areas. This approach is offered at the Warsaw University of Technology based on the interactive learning method – "Case Study". This method directs the learning process towards the practical activities of applicants in real conditions. However, it does not consider the basics of designing functional units for devices that operate in difficult operating conditions.

The study [18] is intended for future specialists in the mechanical engineering industry, and is a STEM project based on the experimental production of alternative types of electrical energy – wind, solar and water. Thanks to the conducted research, large data sets were obtained, which were subsequently used for student training. The result of such a training is to improve an adoption of theoretical and practical materials from professional disciplines. Therefore, it is proposed to use STEM projects for the design of functional units of the mechanical engineering and railway industries.

A comparative analysis carried out by N. Zhaohao has revealed the features of educational policies regarding STEM training of pedagogical personnel in leading countries of the world (USA, Great Britain, Australia). Based on qualitative research methods and comparative analysis, it was established that a common characteristic of the educational systems of the studied countries is the implementation of a national policy to promote a professional training of teachers in the field of STEM education [19, 20].

The key principles of brake mechanisms are considered in [21–23], with a focus on mechanical, thermal and dynamic loads that affect their efficiency and durability. Considerable attention is paid to the analysis of the operation of pneumatic, electromagnetic, and mechanical systems of vehicles. Their impact on the overall safety and energy efficiency of rail transport is assessed. Modern calculation, design, and simulation methods are analysed to optimise the design of brake assemblies and predict their behaviour in operating conditions. However, issues related to the stage of printing models of designed assemblies are not considered in the work.

A study of literature sources [6–9, 15–20] allows to conclude that the proposed approaches to designing 3D objects require further research regarding the creation and testing of physical models, as well as stages related to the production and practical aspects of projects, including the 3D printing of their prototypes.

1.2. The purpose of the research

The main purpose of the presented research is to demonstrate the features of integrating STEM technologies into the professional training of transport engineers, using the example of calculating the tightening of a vertical lever in a brake lever transmission system. This will improve students' understanding of how the unit operates and its loading under operating conditions.

To achieve this goal, the following tasks have been defined:

- Describing the methodology for the computer-aided design of a functional 3D object, using the example of the tightening of a vertical bogie brake lever in the SolidWorks software package,
- investigation of the mechanical properties of the tightening of a vertical bogie brake lever when under operational loads using the SolidWorks simulation software package,
- describing the procedure and printing a three-dimensional model of tightening the vertical bogie brake lever on a 3D printer.

2. Materials and methods

The vertical lever tensioner is an element of the brake lever transmission of a freight wagon bogie designed to transfer the load between its vertical levers (Figure 1).

Now, let's consider the process of creating a spatial model of a vertical lever tightening system. The first step is to construct a two-dimensional component. When activating the two-dimensional sketch mode, the program interface changes. The process of constructing the vertical lever for tightening the bogie of the wagon brake system is performed in stages, modelling all its components and combining them at the finishing stage into one part [24].

It is advisable to start the process of constructing the vertical lever for tightening the bogie with a cylinder. Therefore, in the first step, a cylindrical frame of a closed sketch of a rectangular section with the appropriate dimensions is constructed with the centre at the beginning of the coordinate system and the "Revolved Boss/Base" command is used. After activating the corresponding command in the Command Manager, the numerical value of the rotation angle is entered – 360 degrees.

The next stage is building the fastening system for tightening the vertical arms of the bogie. After entering the dimensions, a flat part of the component of the fastening system will be created. After completing the formation of the flat part of the fastening system, it is necessary to go to the "Features" panel, which activates the operations for creating three-dimensional shapes. A contact area of the appropriate size is formed at the end of the part to coordinate the connection of parts during the assembly. Therefore, the next step is to create an additional plane tangent to the body part. On the created plane, a circle of the appropriate diameter is built in sketch mode. Then, the circle is extruded into the part to the intersection with the line of the flat part. The formed cylinder is cut at an angle in the direction of the connection.

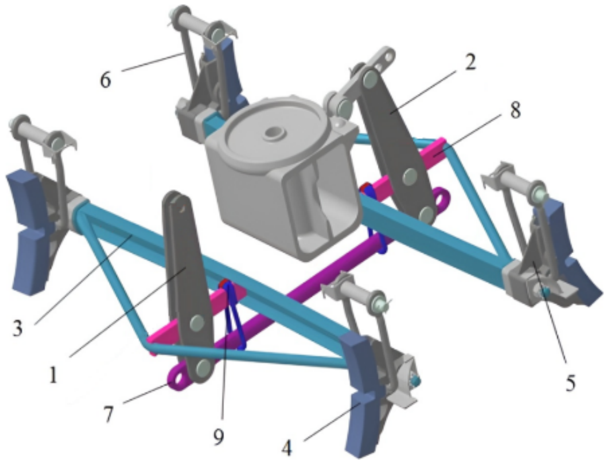


Figure 1. A brake lever transmission of a freight wagon bogie: 1, 2 – vertical levers; 3 – a triangle; 4 – a pad; 5 – a brake pad; 6 – pendulum suspensions; 7 – tightening of vertical levers; 8 – a spacer; 9 – a bracket.

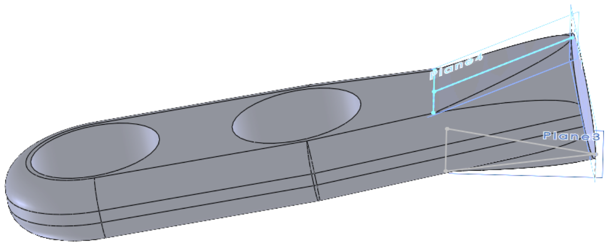


Figure 2. Design of the tightening mechanism of the vertical arms of the bogie.

Since the construction of the cutting zone does not coincide with the main planes, an additional guiding plane is created. A 3D diagram is activated, and the creation is controlled by references to the appropriate points (the centre of the connection line and the contact point on the circle of the top of the cylinder) and a guiding line is built in order to do this. This will create an additional plane. The next step is to apply the "Swept Cut" operation and repeat all the steps for the opposite side of the vertical bogie arm (Figure 2).

The assembly process begins with opening the "Assembly" file. The previously designed parts of the tightening mechanism of the vertical arms of the bogie are opened in the Task Manager. In this regard, the fastening elements are activated in the search log. At the same time, the designed elements are placed in the desired direction and brought closer to the cylinder. The next step is the "Mate" operation. The final stage of the assembly is the operation of adding bushings to the holes in the tightening elements (Figure 3).

Calculating the strength of the tightening of the vertical levers of the bogie, the mechanical part of the brake lever transmission, involves determining the geometric dimensions of the sections. This is because the maximum stresses arising in these sections when loads are perceived during braking should not exceed the

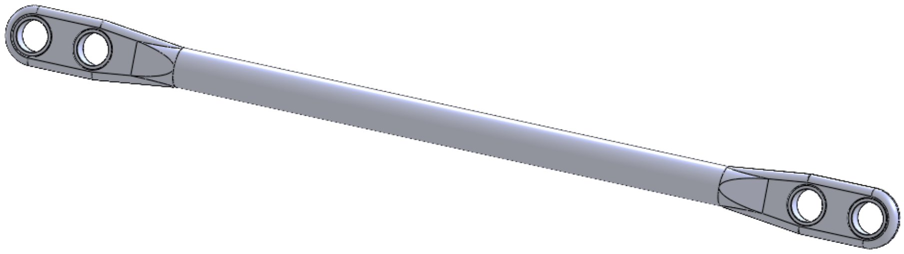


Figure 3. A view of a 3D computer model of the tightening mechanism of the vertical arms of the bogie.

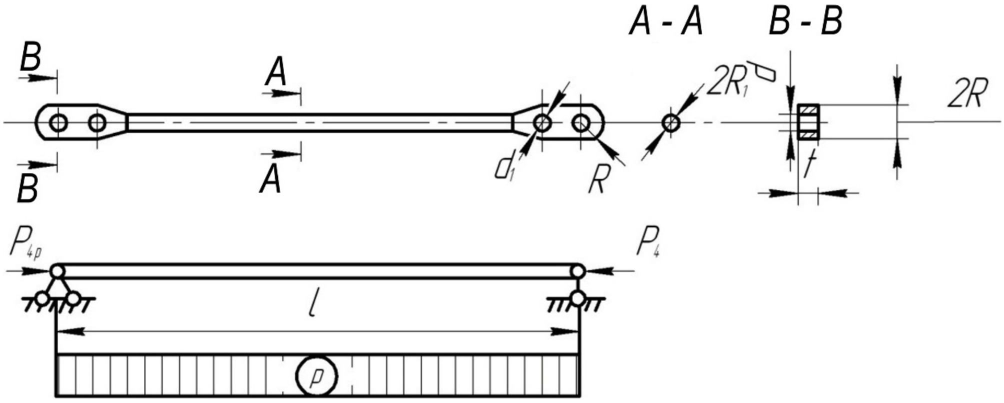


Figure 4. A calculation scheme of tightening the bogie vertical levers and its cross-section.

maximum permissible stresses for the steel used for the vertical levers of the bogie. In operation [25, 26], it is possible to achieve a coincidence of the calculated and normative forces for tightening the vertical levers of the bogie, which is calculated in accordance with the calculation and design standards for strength. Therefore, students are should consider the various options for selecting steel grades when performing calculations to determine the strength required to tighten the vertical levers of the bogie. This will allow the coefficient of longitudinal bending to be determined depending on the greatest flexibility of the rod.

In the calculation scheme, the tightening of the vertical levers of the bogie is represented by rods that are hinged at the ends. Depending on the process of breaking the wagon, these rods can experience tensile or compressive forces (Figure 4).

The tightening of the vertical levers of the bogie is connected to the longitudinal rod via a hinge. The tightening of the vertical levers of the bogie is subject to compressive forces P_4 and P_{4p}. Therefore, it is designed to withstand compression with and undergoes a longitudinal bending check:

$$\sigma_{cm} = \frac{P_4}{F \cdot \varphi} \leq [\sigma_{cm}], \tag{1}$$

where F is the cross-sectional area (excluding local weakening) [m^2] and φ is the longitudinal bending coefficient (in the plane of least stiffness) [27].

The value of φ is determined depending on the greatest flexibility of the rod according to Table 1.

In this regard, students are given the appropriate steel grade for which it is necessary to choose the flexibility of the rod.

λ	**φ** Steel marking St. 3, St. 20	St. 5, St. 30	09G2D
10	0.99	0.98	0.98
20	0.97	0.96	0.95
30	0.95	0.93	0.92
40	0.92	0.89	0.89
50	0.89	0.85	0.84
60	0.86	0.80	0.78
70	0.81	0.74	0.71
80	0.75	0.67	0.63
90	0.69	0.59	0.54
100	0.60	0.50	0.46
110	0.52	0.43	0.39
120	0.45	0.38	0.33
130	0.40	0.32	0.29
140	0.36	0.28	0.25
150	0.32	0.25	0.23
160	0.29	0.23	0.21
170	0.26	0.21	0.19
180	0.23	0.19	0.17
190	0.21	0.17	0.15
200	0.19	0.15	0.13

Table 1. The longitudinal bending coefficient.

The flexibility of the rod is determined by the formula:

$$\lambda = \frac{\beta \cdot l}{\sqrt{\frac{J}{F}}}, \tag{2}$$

where β is the beam length reduction coefficient, determined depending on the conditions of its fastening and load application, l is the calculated length of the rod [m], and J is the geometric moment of inertia of the rod section [m^4].

Figure 4 shows a calculation scheme of the rod fastening, the coefficient $\beta = 1$.

It is important to note that the longitudinal force P depends on the dynamic load when the vehicle is in motion. Therefore, this must be taken into account when studying the strength of vertical lever tightening in dynamics.

The geometric moments of inertia J of the rod section and the cross-sectional area F for a circular section of the vertical levers of the bogie are determined by the formulas:

$$J = \frac{\pi \cdot d^4}{64}, \tag{3}$$

$$F = \frac{\pi \cdot d^2}{4}. \tag{4}$$

The flexibility of the rod for a circular cross-section of the vertical levers of the bogie is determined by the formula:

$$\lambda = \frac{4 \cdot l}{d}, \tag{5}$$

and the diameter of the particular components is determined by the formula:

$$d = 2 \cdot \sqrt{\frac{P_4}{\pi \cdot \varphi \cdot [\sigma_{cm}]}}. \tag{6}$$

Firstly, it is necessary to determine the approximate diameter of the vertical levers of the bogie. For this, tt is necessary to take the value $\varphi = 1$. Then, using the Equation (2) and varying the diameter d, it is possible to select the rod's flexibility value λ, which in turn enables the necessary coefficient of longitudinal bending φ to be selected from Table 1 to specify the tightening diameter.

The tightening diameter of the vertical levers in the bogies of freight wagons, considering the stability from longitudinal bending, must be at least 50 mm.

Assuming that the pressure from the roller is evenly distributed over the inner cylindrical surface of the eye for indirect hinged tightening eyes (Figure 5), the greatest compressive stresses at point A are calculated by the formula:

$$\sigma_{\max} = \frac{P}{d_1 \cdot t} \cdot \frac{4 \cdot R^2 + d_1^2}{4 \cdot R^2 - d_1^2}, \tag{7}$$

valid for the hinged eye $R - \frac{d_1}{2} = \text{const}$.

Indirect hinge eyes in the horizontal levers are calculated in the same way as direct ones for compression according to Equation (8), and for shear according to Equation (9).

Hinge eyes in the vertical levers of the bogie are designed to withstand compression, shear, as well as

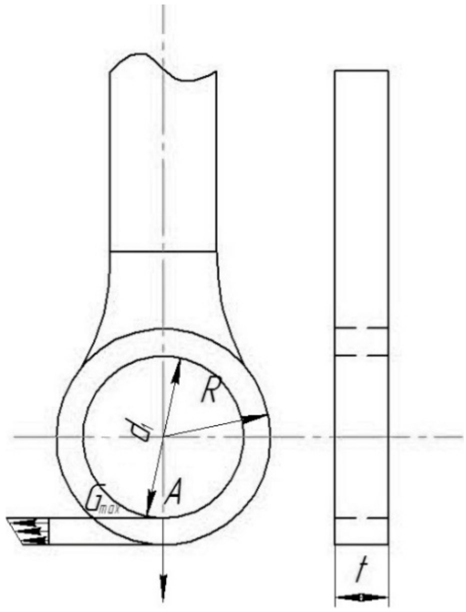


Figure 5. Round hinged eyelet parameters.

for bending and tension. The compression and shear stresses are determined by the formulas:

$$\sigma_{zm} = \frac{4P}{\pi \cdot t \cdot d_1} \leq [\sigma_{zm}], \tag{8}$$

$$\tau_{zr} = \frac{P}{2t \cdot h_1} \leq [\tau_{zr}], \tag{9}$$

where P is the force acting on the eye [N], t is the thickness of the eye [m], d_1 is the eye hole diameter [m], h_1 is the height of the eye section along the cut line (considered the same) [m], at which this height is calculated as follows:

$$h_1 = R - \frac{d_1}{2}, \tag{10}$$

where R is the radius of the outer contour of the eye [m].

In this case, the permissible stress must be considered together with the safety factor. The value for brake lever transmission parts is between 1.4 and 2.0, as set by regulatory documents. For 1 520 mm gauge wagons, for example, the standard [28] can be used.

3. Results

A strength analysis was performed to determine the tightening of the vertical levers of the brake lever transmission. For this analysis, one of the most advanced calculation methods currently employed in mechanical engineering was used, the finite element method [29, 30]. It was implemented in SolidWorks simulation software [31–35]. A finite element model was created to determine the stress distribution and displacements fields during the tightening. The optimal number of finite elements was determined by graph-analytical methods. Since the mesh was created using a solid body, tetrahedra were used as the

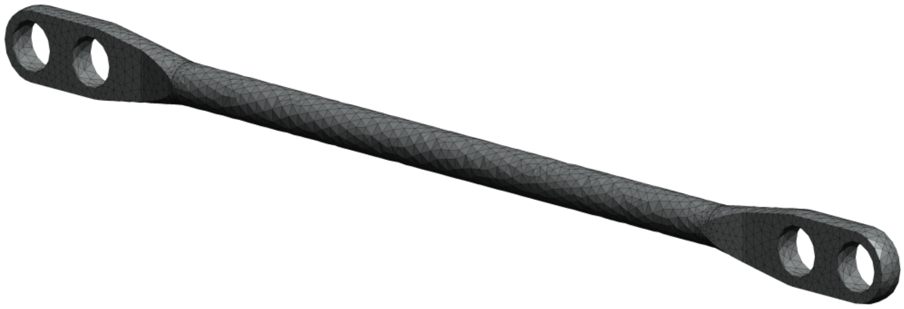


Figure 6. A finite element model of the bogie vertical levers.

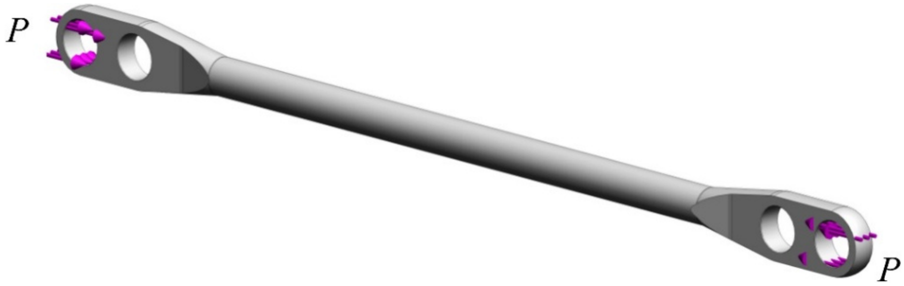


Figure 7. A calculation scheme for tightening the bogie vertical levers.

Figure 8. The loads of the hinged eyelet.

finite elements. Taking this into account, the number of elements in the model was 17 209, and the number of nodes was 41 856. The maximum element size was 10 mm, and the minimum was 2 mm. The finite element model of the tightening is shown in Figure 6.

As one of the most common types of tightening deformation is compression, the calculation was carried out specifically for this scheme. (Figure 7). In this case, the values of these forces were taken as $P = 48.035$ kN, which corresponds to the case of using composite blocks on a wagon [36, 37].

The braking mechanism was fixed in the areas where the rollers were installed. Steel St. 3, which is typical for the manufacture of parts of the brake lever transmission of the bogie, was used as a structural material. The isotropic properties of the steel were considered, which allowed using the Mises criterion as a calculation criterion. The calculation results are shown in Figures 8–10. It was established that the maximum stresses occur in the hinged lugs during tightening (Figure 8) and are 128 MPa (Figure 9). The achieved stresses are 11.7 % lower than the permissible ones, which, according to the data of Table 1, which is in [28], are 145 MPa. Therefore, the strength of the tightening is ensured.

The maximum movements in the puff occur in its end parts. However, they are quite insignificant and amount to less than 1 mm (Figure 10).

At the last stage of the design, a physical prototype of the digital model is made using 3D printing, which includes: preparing the printing file, selecting appropriate materials, setting up the 3D printer, the printing process, and resolving potential problems that may arise during printing. The previously designed model is exported to the (*.stl) format for subsequent slicing into layers in the appropriate software (Figure 11).

The model has edge fillets, which makes it very easy to manufacture by casting. However, due to the nature of FDM printing, the fillets of the printed part will have noticeable steps, as the slicer attempts to approximate the radius of rounding with layers of a fixed width. Reducing the layer thickness will mitigate this effect. However, this will significantly increase the printing time (Figure 12).

A variable layer thickness can be applied to achieve a satisfactory result of printing the part, which will

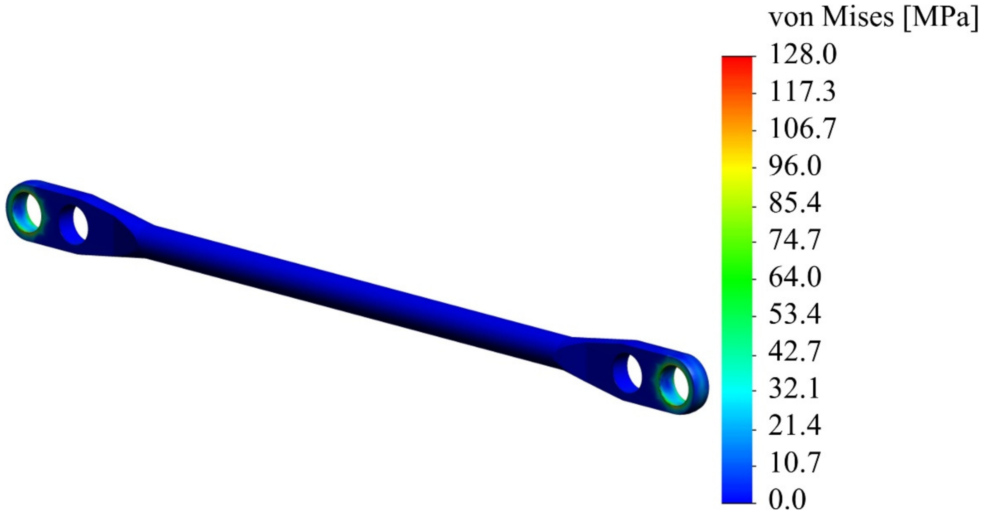


Figure 9. Stress distribution in the hinged eyelet.

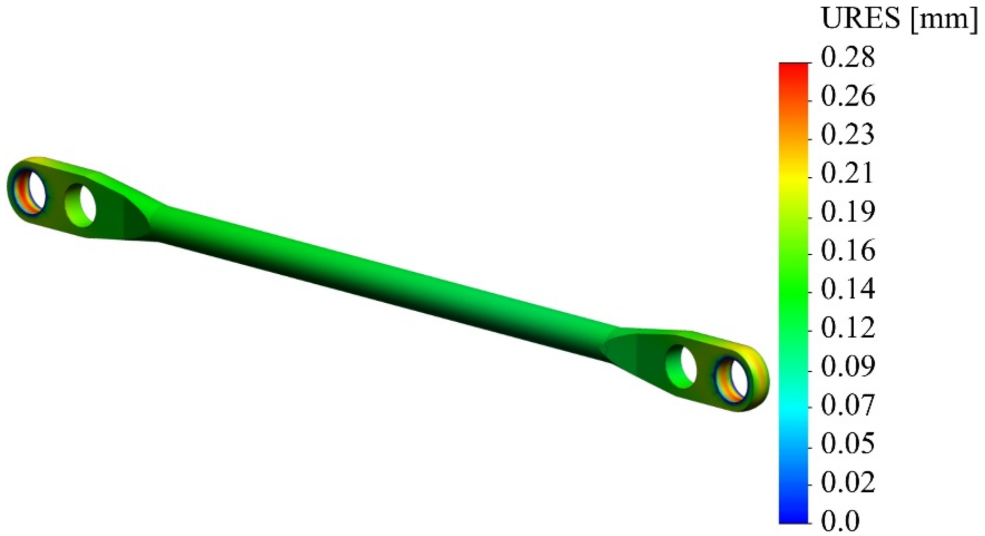


Figure 10. Displacements of the hinged eyelet.

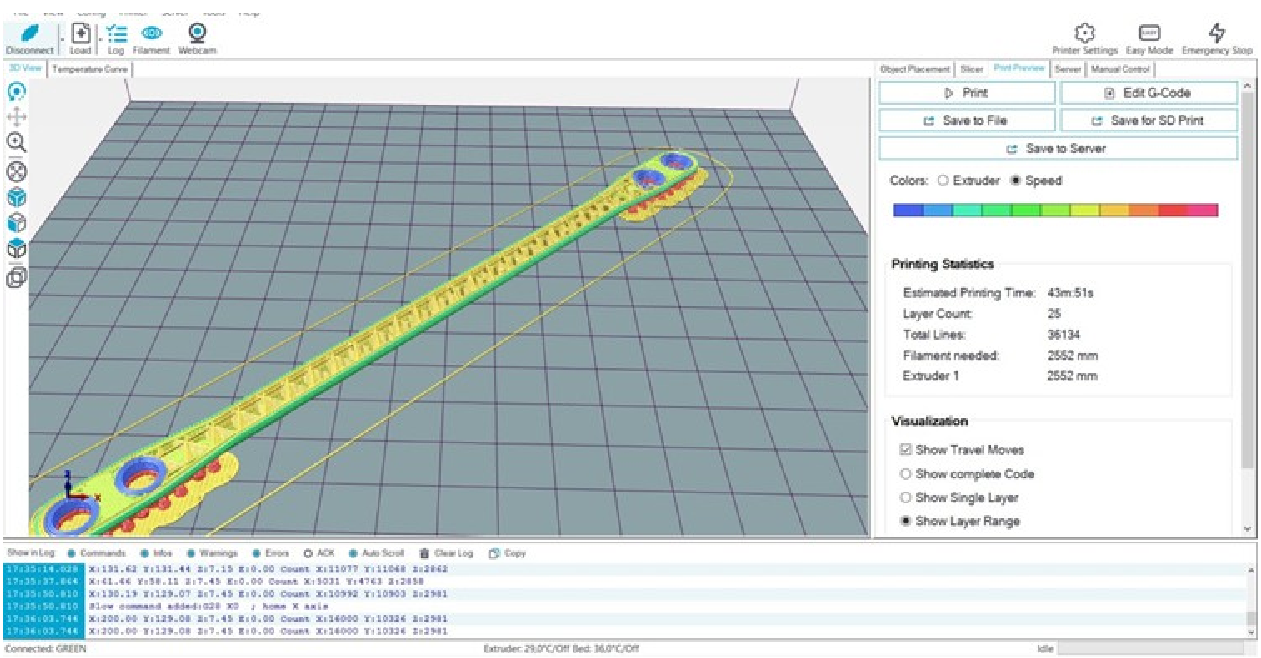
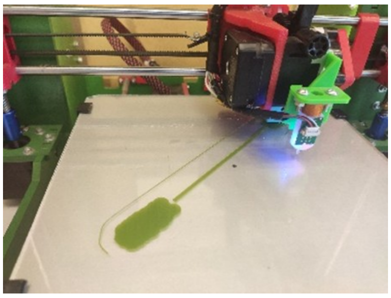
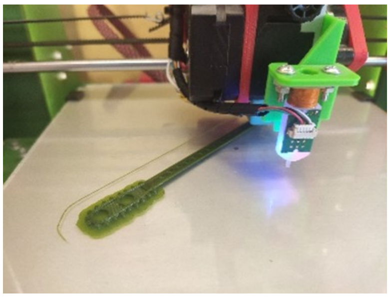


Figure 11. Visualisation of the vertical lever tightening print in the Repetier-Host programme window.



(a).



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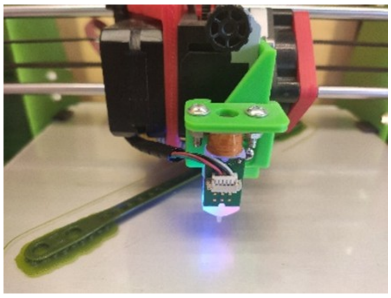

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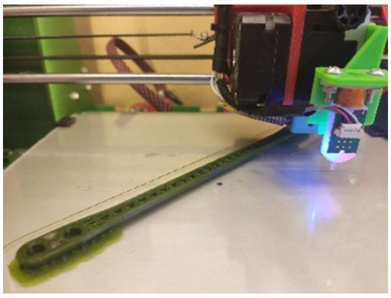
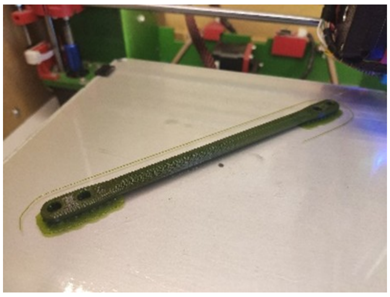


(d).



(e).

(f).

Figure 12. The printing process of the bogie vertical arms: a – an initial stage; b to d – an intermediate stage; e – a final stage.

allow the slicer to reduce the layer thickness in areas of the model where greater detail is required. That is, for example, print the vertical walls with a layer thickness of 0.25 mm and fillets with a layer thickness of 0.1 mm. This will reduce the effect of steps, and get a printed part closely resembling a model cast from metal. The process of visualising the printing speed and the printed 3D model of the vertical arms of the bogie are shown in Figure 12.

The quality control of 3D printing the models can be further controlled by digital processing of their images. This project will enable future teachers not only to master technical knowledge, but also to apply engineering approaches to solving practical problems, which is an important aspect in the preparation of qualified applicants.

4. Discussion

Working with students within the framework of special disciplines related to transport design has revealed that they struggle with strength calculations for various vehicle components. This highlights the need for solutions that faciliate students' understanding of this material. One possible solution is the use of STEM technologies in the educational process.

The design, calculation and 3D printing features of tightening the vertical levers of a freight wagon bogie are highlighted to promote integrating STEM technologies into the professional training of transport engineers and vocational education teachers. A detailed description of the modelling process in the SolidWorks software package is provided (Figure 2). The strength and stability of the braking mechanism as a rod system are calculated (Figure 4). The stress and displacement distribution fields during tightening were determined using the finite element method, which is implemented in the SolidWorks Simulation software package (Figures 9–11). Based on the created spatial model of the mechanism, its physical model was made using 3D printing (Figure 12).

The results of this study have certain advantages compared to those analysed in this work, namely, a methodology for creating a three-dimensional braking mechanism model is proposed, which provides a standardised approach to STEM design. This is quite important when teaching transport engineering disciplines in higher educational institutions, as it allows students to develop the ability to solve complex specialised tasks, as well as to solve practical problems in professional practice or help them in the process of further training using the theories and methods of technical sciences.

It should be noted as a limitation of this study that when calculating the strength of the tightening using the finite element method, the friction forces that may arise between the tightening lugs and rollers were not considered.

The disadvantage of this study is that the authors considered only the normative values of the loads acting on the mechanism during braking. That is, the calculated values of operational loads, which may differ from the normative ones, were not taken into account. However, due to the fact that this work is aimed at highlighting the general methodology for calculating the tightening forces, this drawback is not significant and can be considered as a further perspective of this study.

The developed methods and results have practical significance for engineering disciplines, particularly in the fields of mechanical engineering, transport systems, and automation.

5. Conclusion

(1.) It is proposed that STEM technologies be used in the educational process to help students understand the issues related to the operation and loading of vehicles. As an example, the process of tightening the vertical levers of the brake lever transmission of the Model 18-100 freight wagon bogie was considered.

The analysis and development of an algorithm for creating three-dimensional models of objects made it possible to build a standardised STEM design system, which is a powerful tool for teaching technical disciplines. It considers modern approaches to parametric modelling based on the integration of geometric, physical and functional characteristics. The use of this algorithm allows you to reduce the likelihood of errors at the stage of creating a digital model, which is an important factor in complex engineering systems. The methodology is focused on improving the design process, taking into account the requirements for energy efficiency, mechanical reliability, and manufacturability.

(2.) The use of the finite element method during STEM design to model the mechanical properties of the object provided a deep understanding of the behaviour of the mechanism under operational loads. The use of the SolidWorks Simulation software package made it possible to determine the distribution of stresses and displacements in the zones of the horizontal levers of the brake lever transmission of the freight wagon bogie. During the research, it was found that the maximum stress values of 128 MPa occurred in the hinged lugs of the vertical arms of the bogie. These values are 11.7 % lower than the permissible stress level of 145 MPa, as given in the standards. Given the results obtained, it can be stated that the strength of the mechanism is ensured, since the maximum stresses do not exceed the maximum permissible values, which confirms its structural stability and reliability under operational loads. The analysis confirmed that the proposed mathematical models could be used to predict the resistance of the object to dynamic and static loads. This is the basis for optimising and rationalising the structural characteristics and choosing materials capable of providing the necessary safety margin.

(3.) A full manufacturing cycle of a prototype for the vertical arm mechanism of the bogie was carried out using the additive manufacturing method, confirming the practicality and accuracy of the digital models designed in the SolidWorks software package. The results obtained showed that the use of 3D printing is an effective tool for the rapid creation of prototypes and the verification of their compliance with structural and functional requirements.

It is expected that students will have a better understanding of the educational material when this approach is used in teaching activities within transport design disciplines.

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