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Tests and Analysis of the Rigidity of a Safety Fence

Banas P.*
Poznan University of Technology, Poland
*corresponding author

Annotation. Today's Industry 4.0 requirements, including production automation, necessitate the securing of production lines to ensure maximum safety for employees. This article presents a solution for fastening systems in safety fences used on production lines. The main objective of the research was to compare the rigidity of the entire fence, i.e., a set of different elements, depending on the fastening system used for the mesh panel and fence post, based on simulation tests. Both commercially available solutions and own solutions were compared. The parameter for evaluating the solutions is the maximum displacement value, which is derived from computer simulation and allows for an estimation, within a certain range, of the behavior of the system under real conditions. The maximum displacement values recorded during the simulation range from 14 to 20 mm. Achieving the appropriate level of fence rigidity is required to ensure safety on the production line, and the use of an appropriate solution allows for an increase in safety and working conditions. The analysis carried out allowed the behavior of the object as a result of the force to be estimated, but it completely ignores material aspects and factors such as heat distribution, vibrations or parameters that vary in reality, such as the condition of the material, temperature, or the environment in which the tested object is located.

Key words: safety fence, fastening systems, safety, MES, production, industry 4.0

Introduction

Nowadays, production activities are becoming more automated [1] and the presence of machines on production lines is commonplace [2]. Since not every production line can be fully automated, the human factor is still present in most plants [3]. The presence of machines and people in the same plant, on the same production line, poses a certain danger [4]. The work area for each group should be properly planned and designated within the plant in order to avoid undesirable incidents.

One method of securing the working area of industrial machinery is the use of safety fences [5], which allow the machine's working area to be separated from the human working area. This eliminates the accidental possibility of an unwanted element entering the machine's working area on the production line. This increases safety in the production plant and protects expensive machines from breakdown or damage. The main role of safety fences is to prevent the operator from contact with the machine during its operation, although they can also perform other tasks. Guards are designed to separate the safety zone and prevent access to the danger zone. Fences should be designed in a way that is reliable and does not allow unauthorized access to restricted areas when it is dangerous or unauthorized. There are also sensor-based solutions that are designed to detect human presence in the exclusion zone and can control the operation of devices in a designated area [6], although this solustion do not effectively protect against many physical hazards. There are also combinations of classic solutions with modern algorithms to increase safety [7].

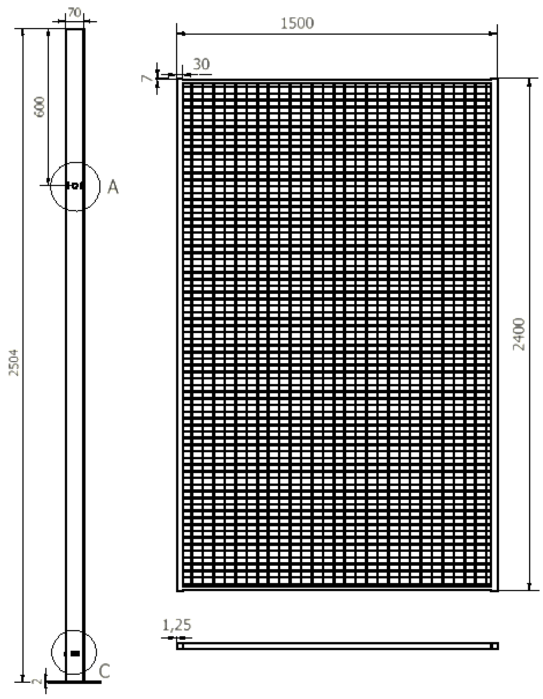
When used in work areas where there is a risk of material, objects, or fragments being ejected, due to the nature of the work and the technological process, fence must ensure safety for the operator and other potentially endangered persons. The guard usually performs two main functions, which are to prevent personnel, objects, or other persons from accessing the danger zone and to stop parts of the machine, including workpieces, in the area protected by the guard [8]. Safety fences are characterized by several parameters [8] according to which their safety can be assessed. First of all, these are its dimensions, i.e., thickness and width, as well as the very important height. Another parameter that is important in terms of safety is the design of mesh panels, which, due to the environment of a production line, often cannot be full covers and must ensure good visibility. Therefore, fence panels are most often made of thin, welded bars. The density of the fence translates into the required distance of the fence from the danger zone and its strength. The rigidity of the fence is essential for the safety of the protected area and its surroundings, protecting the environment from sources of danger and the consequences of an undesirable event, such as flying debris.

The main objective of the research was to compare the rigidity of the entire fence, i.e., a set of various elements, depending on the fastening system used for the mesh panel and fence post, based on simulation tests. There is also a proposition of own concepts for fastening safety fences, which have the potential to streamline the fence installation process while maintaining all safety standards. The analysis was performed on the basis of computer simulation in Autodesk Inventor, where the displacement of materials after applying a force of 2000 N to the side surface of the mesh panels was evaluated. Performing this type of analysis is necessary in order to examine the ability of an object to perform its intended function [9–10]. The program itself is a proven and widely used tool that utilizes pre- and post-processors for graphical engineering interpretation, where the computational model can be described by solid and surface elements [11–12]. The main novelty presented in the article is our own concept of a fastening system, which is characterized by better parameters in terms of assembly and low production costs, giving it a significant advantage over competing solutions.

However, it should be remembered that achieving high strength parameters for a fence may involve high production costs related to the technological process of manufacturing the components, the necessary materials, and the method of processing. The solution should ensure high strength parameters at the lowest possible and reasonable production costs [13–16].

1. Materials and methods

Conducting an economic analysis allows for a preliminary estimate of the manufacturing costs of the tested safety fence model, which in itself should be optimized in terms of production price, have appropriately selected tolerances and surface treatment in order to achieve a favorable manufacturing cost [17]. The selected fastening concepts should also be tested for strength in order to determine the solution that will ensure the greatest rigidity of the fence. The rigidity of the fence is essential for the safety of the protected area and its surroundings, protecting them from sources of danger and the consequences of an undesirable event, such as flying debris from broken machine parts. The analysis was performed on the basis of a computer simulation in Autodesk Inventor, where the displacement of materials after applying a static force of 2000 N to the side surface of the mesh panels was evaluated. The model was recreated in a computer program, where a simulation was performed during which the assumed force was applied, taking into account the effect of gravity. All fastening system solutions are installed at the same height, i.e., 1904 mm from the base of the post and 1800 mm from the base of the mesh panel, which is ¾ of its height. The fence model (Fig. 1) is the same for all three considered solutions for fastening the mesh panel and fence post.



(a) (b)

(a) fence post; A – mounting system installation point, C – mesh panel mounting point on the post, (b) mesh panel

Fig. 1. Model of the tested safety fence

Safety fence should have a simple and economically justified design [15]. It is advantageous for the fence to be simple and quick to install and to require the smallest possible number of operators [16]. The paper presents three concepts for a mounting system: concept 1 is a solution commonly used in industry, while concepts 2 and 3 are original solutions.

1) Concept 1 – metal clamps

There are many ready-made solutions on the market, one of which is metal clamps (Fig. 2). This is one of the most commonly used solutions and involves the use of metal clamps that grip the mesh panel and are attached to the pole, using a screw connection between the clamp and the pole and between the clamp and the mesh panel. This solution is simple in design and manufacture, but requires specially designed screws and a lot of work during installation. A very advantageous feature of this solution is its low manufacturing cost, although separate structures for intermediate and angular connections must be taken into account (Fig. 2). The solution with a metal bracket is simple in design, but requires more steps during installation and increased labor during the preparation of elements for installation. There is also an increased number of parts, and the screws must be designed in such a way that the fasteners cannot be completely disconnected. The design of the system must not create a risk of losing any of the components of the fastening system.

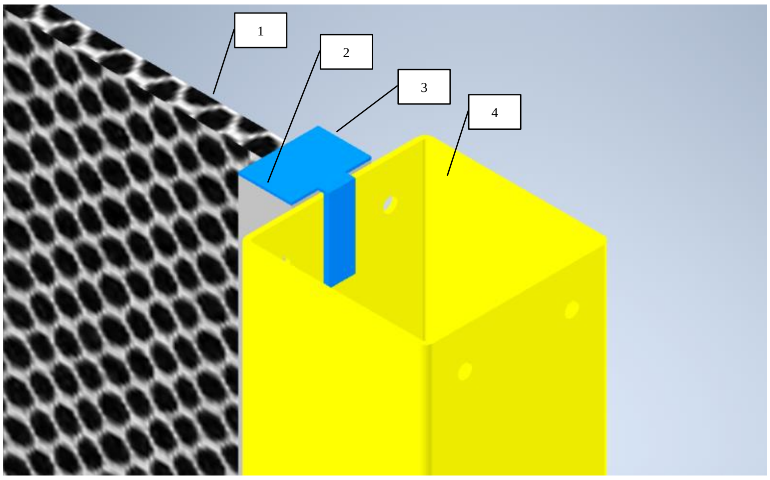
(a) (b)

Fig. 2. Metal clamps available on the market; (a) clamp for indirect (parallel) connections, (b) clamp for angular (perpendicular) connections

2) Concept 2 – snap-on caps

The second concept, which is our own solution, is the use of a cap with a snap-on mechanism, mounted at the end of the mesh panel in contact with the post (Fig. 3). The cap utilizes the deformation of the material during pressing, which is caused by the overlapping geometry of the objects. When the cap is fixed at the correct height, the snap closes, fixing the position of the post and the mesh (Fig. 4.). Disassembly involves inserting a tool that allows the latch to be pulled away from the geometry on which it was locked.

Fig. 3. Model of a snap-on cap used to connect a mesh panel to a post

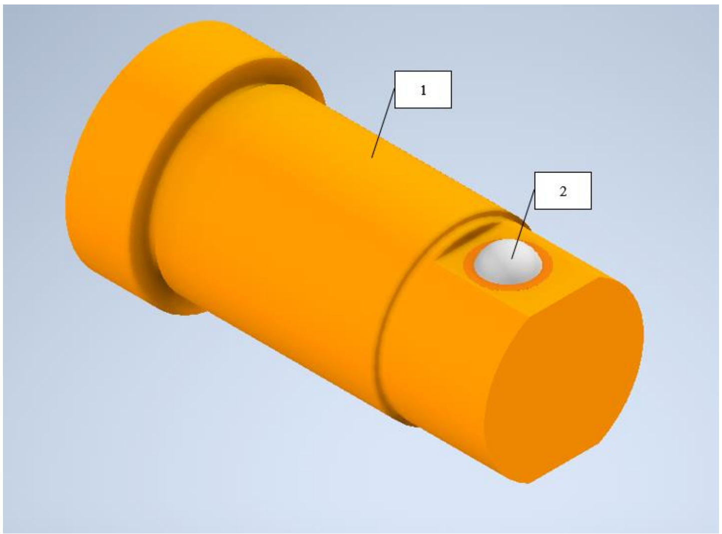


1 – mesh panel, 2 – mesh panel profile, 3 – snap-on cap, 4 – fence post

Fig. 4. The concept of using a snap-on cap as a fastening system in safety fences

3) Concept 3 – mounting pin

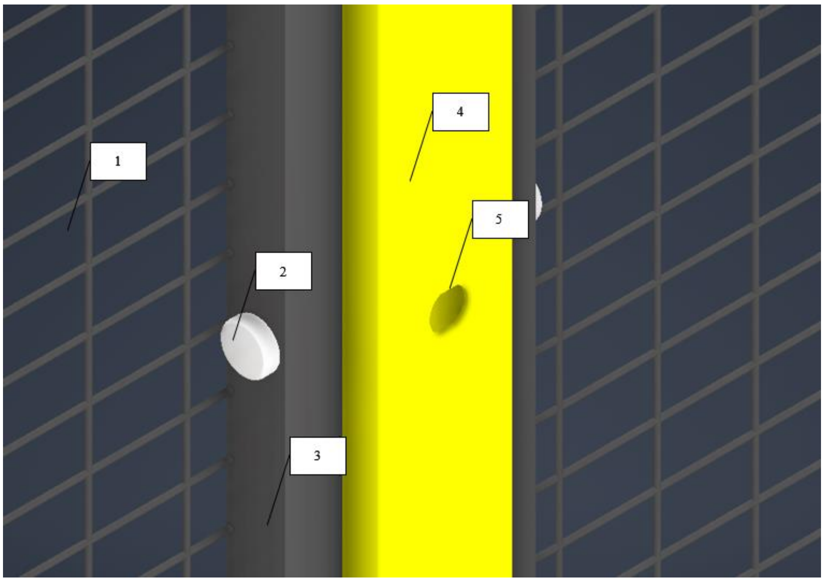
The third concept, also our own, is a connection using a fixing pin installed in the pole structure or mesh profile. It allows for a simple design and quick installation. The mesh panel support profile has a hole that allows the pin with a tool hole to be inserted and locked in place in order to release the lock during disassembly (Fig. 5).



1 – pin, inserted into the installation hole, 2 – double-sided latch

Fig. 5. Mounting pin with latch

The solution using a mounting pin allows for quick installation, but requires a specially designed tool for removal. The pin itself must be permanently connected to the post by pressing it in. The pin must be installed in such a way that it can be removed from the inside of the protected area to allow for removal once the security fence is fully assembled. The pin, when installed in the socket, passes through the cutouts in the mesh profile and the fence post, resulting in a snap-in effect after passing through the last hole in the post. The advantage over metal clamps (Fig. 2) is that the element is less visible from the outside, which translates into better transparency of the mesh panels due to less visibility restriction (Fig. 6).

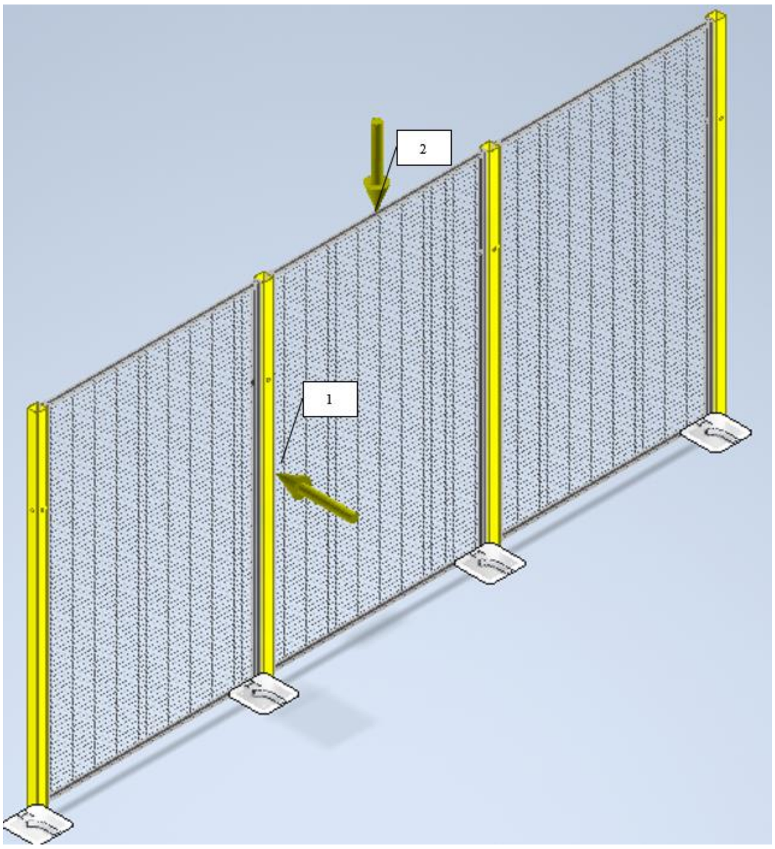


1 – mesh panel, 2 – mounting pin, 3 – mesh panel profile, 4 – fence post, 5 – cutout for mounting pin in the post

Fig. 6. Installation of mounting pins in a safety fence

Another advantage of this solution is the possibility of installing the mesh panel on either side of the pole, as the holes required for installation can be made on either side of the pole as needed. This translates into lower production costs, as only one type of pole, one type of mesh panel, and one type of pin are manufactured.

During the simulation, a fence model was prepared (Fig. 7), whose structural changes resulted solely from the fastening system used. Each model consisted of four fence posts, three mesh panels, and the number of fasteners required to connect the mesh panels and posts. In addition, each fence was subjected to the force of gravity to bring the simulation results closer to reality, and a static force of 2000 N was applied to the entire side surface of the panel profiles.



1 – force of 2000 N acting on the side profile of the panel, 2 – force of gravity loading the fence

Fig. 7. Model of a safety fence with forces acting on it

The main parameter assessed in the simulation was displacement, where the displacement of the point furthest from the initial position was evaluated and, on this basis, the stiffness of the fence was assessed. This value was read by the program used to model the fence and perform the simulation.

2. Simulation results

The first simulation (Fig. 8) was performed for concept 1 – intermediate and angular clamps. The fully reconstructed fence, which uses clamps as a system for attaching mesh panels to posts, results in a panel displacement of 17.427 mm when a force of 2000 N is applied to the surface of the mesh panel frame. However, the main advantage of this solution in terms of strength is the possibility of using an increased number of fasteners. This is more advantageous due to the increased rigidity of the structure, but it requires more time for installation and more work by the operator, and increases the cost of purchasing clamps. The simulation result using three pairs of clamps on each fence post (Fig. 9) shows a reduction in the maximum displacement of the fence by almost 3 mm compared to the first simulation tests for the solution with one pair of clamps.

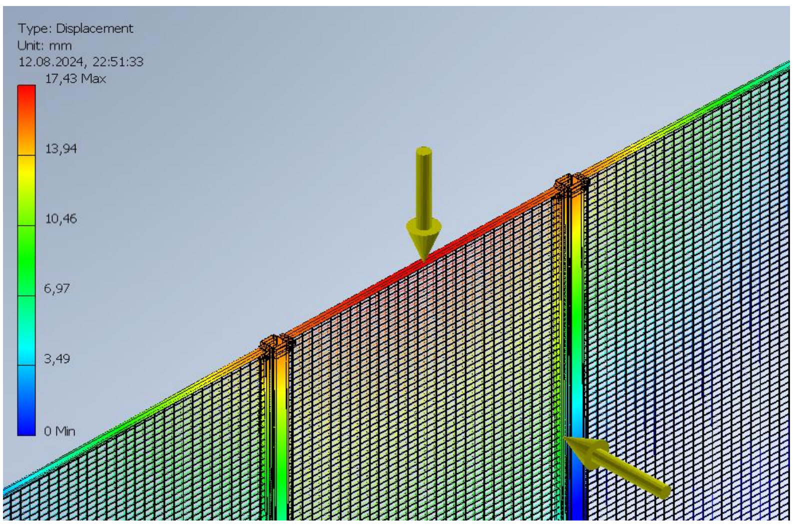


Fig. 8. The results of simulation strength tests for a fence fixed with one pair of clamps

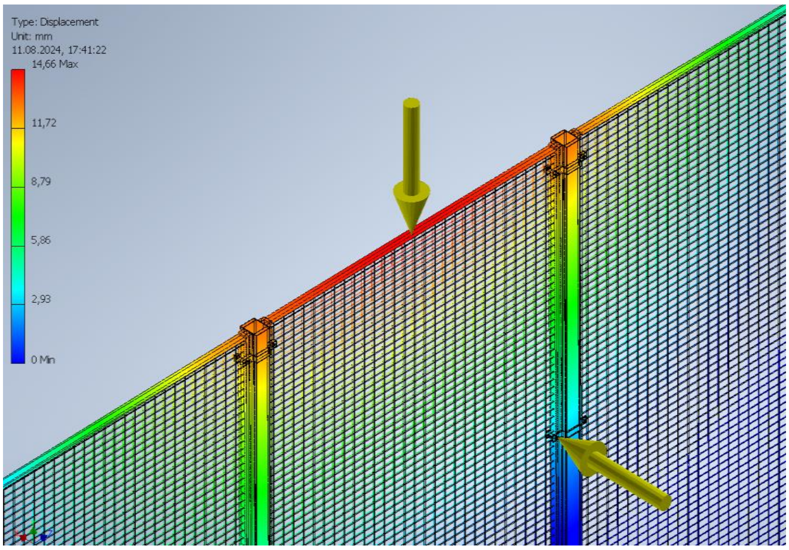


Fig. 9. Results of simulation strength tests for a fence fixed with three pairs of clamps

Based on simulation tests for fencing using caps (Fig. 10), i.e., the second concept, similar results were obtained as for clamps, but due to the method of installing the caps, it is not possible to use multiple caps to increase the rigidity of the fence.

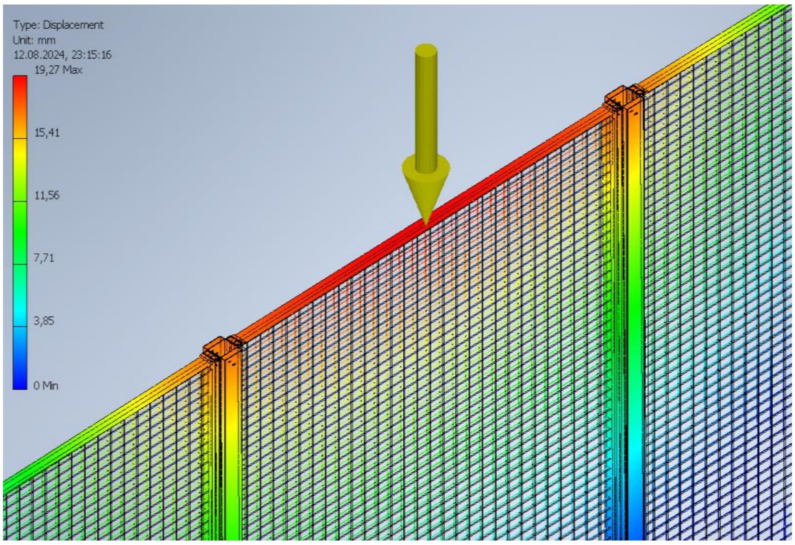


Fig. 10. Results of simulation strength tests for fencing secured with caps

After applying a force of 2000 N and gravitational force, the maximum displacement equal 19.27 mm was obtained. This is a displacement that is almost 2 mm greater than the previous solution, which was based on a single pair of clamps, and almost 5 mm greater than the solution with three pairs of clamps.

The fastening pins, which constitute the third concept of the fastening system solution, can be used multiple times to achieve higher fence rigidity. The results of the simulation (Fig. 11) carried out on a fence using this element show that the maximum displacement value is almost the same as for a single pair of fastening clamps and amounts to 17.432 mm. No simulation was performed for the solution with multiple fastening pins because the data collected so far allows us to predict its results. However, it is worth noting that although the maximum displacement value itself is comparable, the pin is a more advantageous solution in terms of strength, not because of the rigidity of the fence, but because of its inherent durability. Metal clamps are made of bent thin sheets of metal. The pin, on the other hand, is turned from a thick metal rod. Resistance to deformation and stress will therefore be significantly greater for the pin than for the clamps. Therefore, it is worth considering mounting pins as a more durable solution, while ensuring the same level of fence rigidity.

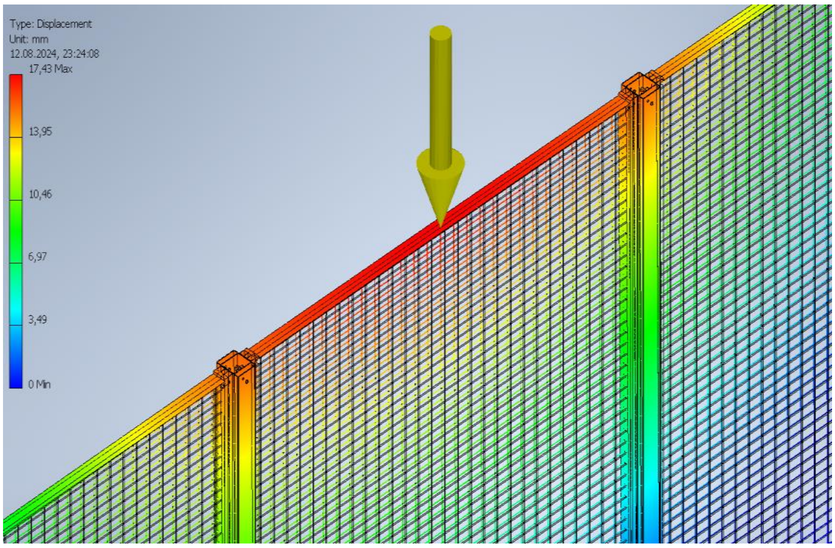


Fig. 11. Results of simulation strength tests for fencing fixed with pins

From the data collected (Fig. 12) from the strength simulation, the lowest maximum displacement value can be observed for three pairs of clamping collars. There is only a slight difference in maximum displacement between one pair of clamps and the fastening pins, with the clamps being significantly cheaper, but less advantageous in terms of the assembly process and strength considerations. The cap provided the least rigidity for the fence.

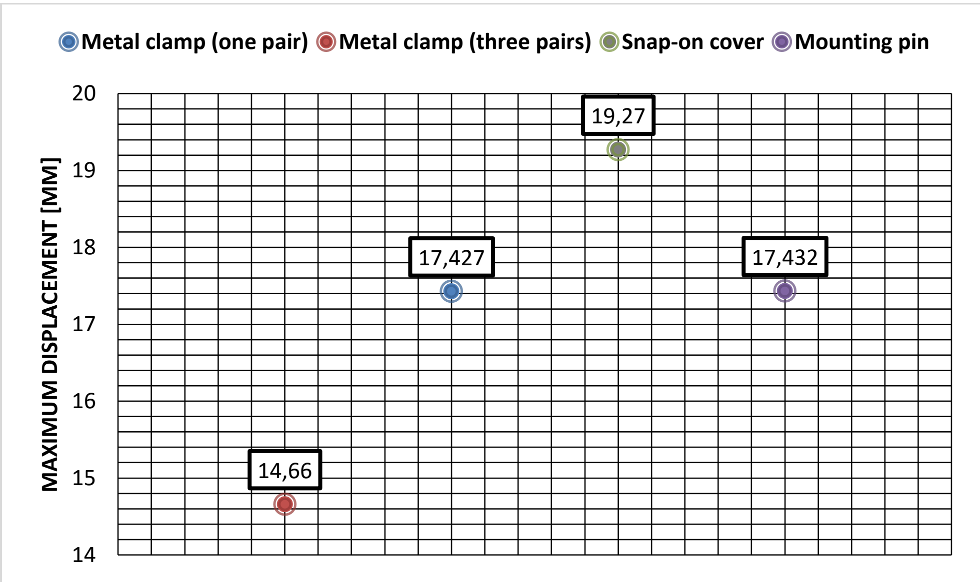


Fig. 12. Maximum displacement chart for simulation tests performed

3. Economic and ergonomic analysis

The fastening system solution in safety fencing should be economically justified while ensuring adequate strength and ergonomic installation, where one of the key features is the number of operators required for installation, installation time, and availability of installation components. Poor ergonomics, on the other hand, can cause musculoskeletal strain [17-19].

The metal clamps used in the first concept of the fastening system require the use of two or three types of clamps: intermediate, angular, and end clamps. Clamps are one of the most common solutions, which is why their purchase price is very low at wholesale prices. It is unlikely that starting your own production of these elements would result in lower or even the same costs of erecting a fence. Especially since three types of clamps may be required to build a fence, in-house production of these elements will almost certainly not be cost-effective for single or small-batch production. Therefore, it remains to purchase clamps from the market, which are affordable. It was assumed in the work that multiple clamps could be used. However, even when using single pairs for assembly, this is a solution that will probably require the most time during installation. This is due to the design of the clamp, which consists of two elements that must be permanently connected to each other. After placing the mesh panel between these elements, the clamp must be tightened properly to prevent the panel from shifting or becoming loose. Each clamp must be fixed at the correct height of the fence. If appropriate markings have been made on the posts or fixing holes, this will speed up the operation. However, one pair of threaded connections must be screwed onto each pair of intermediate or angle clamps. The operation would be much faster with the use of a suitable electric device, but this requires having it in your equipment. The fence can be installed by a single operator with proper planning of the operation and assembly activities, but this can be significantly more difficult. Mounting the mesh panel on a support element does not ensure that all degrees of freedom are eliminated. The panel may rotate and fall out of its axis, posing a risk of injury to the operator. In addition, intermediate and angle clamps should be installed with two adjacent mesh panels placed on the supporting elements. For this reason, a second operator may be required during installation for this fence model. Installing a fence using clamps may require specialized tools to speed up the process. This solution also does not offer the possibility of quick disassembly and will be as complex as installation. This is certainly the solution with the worst ergonomics; despite its low production cost and simplicity of construction, it does not offer the possibility of quick and easy installation.

The snap-on cap presented as the second fastening system concept has a complex design, and the material used must have elastic properties to ensure proper functioning of the fastening element. Depending on the technology used, its production can be very costly. Manufacturing the cap by injection molding involves significant costs in the form of purchasing the appropriate equipment and making the injection mold. For small-batch production, it is more advantageous to use the injection molding services of an external company, but this requires an injection mold, which is very expensive to manufacture. The price of the material itself is low compared to the costs associated with this technological process. Therefore, this solution could be used in mass production, where the cost of starting production is not so significant due to the planned sales horizon and production volume. Caps offer much faster installation, but their installation involves difficult access to the installation area. It is necessary to reach the upper end of the mesh panel profile in order to install the cap, which snaps into place. This can be done by a single operator, as they are able to install the mesh panel on the support element, climb onto a step or ladder, and install the cap. This is not the safest solution, but it is definitely possible. The installation of the cap itself consists only of inserting it into the mesh panel profile, after adjusting its angle relative to the post profile, lowering it, and snapping it onto the profile. A step or ladder will definitely be needed. This may not be necessary for safety fences of lower height. For the disassembly process, a ladder or step stool should again be used to provide access to the area for the disassembly tool, which must be inserted to knock the latch out of the post geometry before disassembling the mesh panel. This is a favorable solution in terms of installation, but the main disadvantage is the need to use a step stool or ladder for tall fences.

The third concept based on a mounting pin is a solution whose cost is comparable to that of metal clamps, and is slightly higher or almost identical to the cheapest solution on the market presented in the first concept. The cost of purchasing materials, processing, and all technological processes that must be carried out in order to obtain a finished component for assembly can be significantly reduced. As a result, the cost of production of the component is very similar to that of metal clamps, with the possibility of starting your own production, which will be justified even for small-batch production. This is due to the availability of the tools necessary to manufacture this element, mainly a hydraulic press and a CNC lathe, which, unlike the injection mold mentioned in the second concept, can be used for other projects or sold after production is completed. The installation of pins, i.e., the third concept, differs slightly from the installation of a cap, i.e., the second concept, and also requires at least one operator. It is still a relatively simple process that can be carried out fairly quickly. The only thing you need to do is insert the pin into the mounting holes after determining the position of the mesh panel. The disassembly process is similar to that described in the concept with a mounting cap and consists only of releasing the lock from the pin and sliding it out of the hole in the fence post. This solution is therefore the most advantageous in terms of the ergonomics of installation and removal. Like the other concepts, it requires the use of tools, but does not require a step ladder or ladder and allows for quick installation and removal.

Table 1 contains a multi-criteria comparison of the concepts under consideration, compiled on the basis of analyses and simulations. Each aspect is assessed on a scale of bad, good, and very good. A poor rating means that the solution has the worst rating for the selected parameter among the concepts under consideration; the opposite applies to a very good rating. A good rating places the solution in the middle or in the same position as other solutions with the same rating for the aspect under consideration. Based on this table, it is possible to quickly identify the solution that best reflects the consumer's needs depending on their situation.

Table 1. Multi-criteria comparison of solutions

Solution	Strength	Cost	Ergonomics
Concept 1	Good	Very good	Bad
Concept 2	Bad	Bad	Good
Concept 3	Very good	Good	Very good

Conclusion

The article presents the results of simulation strength tests for selected concepts of fastening systems in safety fences. Based on the tests conducted and the results obtained, the following conclusions can be drawn:

1. The use of one metal clamp allowed for a maximum displacement of 17.427 mm;
2. The use of multiple clamps allowed for the greatest reduction in displacement, bringing it down to 14.66 mm;
3. The mounting cap achieved the worst result of all, with a displacement of 19.27 mm;
4. The mounting pins allowed for a displacement value similar to that of a single pair of clamps, with a slight, barely noticeable difference in favor of strength considerations;

5. Mounting pins and clamps can be used in multiple quantities to significantly increase the rigidity of the entire fence, although this entails higher construction costs and requires more manpower during installation;
6. Pins are a more robust solution compared to clamps, as their construction is more durable and resistant, and the system consists of fewer components.

Based on the simulations and analysis carried out, mounting pins can be considered the most advantageous solution, both in terms of strength, economy, and ergonomics (Table 1). They ensure high fence rigidity, higher than all others considered in this study, and additionally have high inherent resistance to loads and stresses. What is more, their production method does not involve complex technological processes that require increased financial outlays. Although metal clamps are certainly a cheaper solution in economic terms, they require the design and production of three versions of the same element: intermediate clamps (parallel connection), angle clamps (perpendicular connection), and end clamps (located on the last post in the fence). The pin is manufactured as a single design solution for all types of connections. Caps are also not economically advantageous due to their complex shape and construction. They require injection molding, which is associated with high start-up costs and is completely unprofitable for small-batch production. For ergonomic reasons, no solution can match snap-on caps, which are the fastest to install, but properly prepared posts and panels can be connected just as quickly using pins.

The test results and analysis of solutions are sufficient to consider the mounting system solution using mounting pins to be inexpensive, robust, and easy to install. Based on this knowledge, a suitable design can be prepared for further testing. This design can also be left for further development without yet moving on to the production stage. The right direction for development would be to refine the pin design so that the latch release system is already inside it and only requires the use of a special tool to release it, which will allow unnecessary interference with the pole structure to be avoided. This is because the current solution provides for special holes to allow the pin to be removed. Therefore, it is worth optimizing the design in terms of assembly efficiency (DFA), reducing the number of assembly and disassembly operations and simplifying them. It is also possible to adapt the design of the fences themselves to different assembly methods, which do not necessarily require human involvement. Fence installation can be robotized to eliminate or reduce the need for human labor. The implementation of Lean Manufacturing should also be considered in order to continuously improve processes, eliminate material waste, and improve production efficiency.

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Information of the author

Banas Piotr, Eng., M.Sc student, Poznan University of Technology
e-mail: piotr.banas@student.put.poznan.pl