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GRAPHIC MODELLING AND DESIGN OF A LOCKING SYSTEM USED FOR MODULAR BUILDINGS

Abstract: *The paper presents an interlocking system designed to fix and hold together the panels of a modular house. The house modules are flat square panels, almost identical, which need to be hold using a locking system. The locking system is a simple, but solid construction, capable to resist to repeated assembling and disassembling operations. It consists of some linkage mechanisms and a ratchet; it is hand-powered in order to ensure a fast mounting of the panels. In this paper are presented all the steps necessary to be followed and the restraints of the design process.*

Key words: *Locking mechanism, linkage, modular building, ratchet mechanism, virtual modelling.*

1. INTRODUCTION

Modular constructions present a number of advantages, this being the reason why this solution is widely used in modern design, and not only. A modular construction is simpler, because the variety of components is smaller. It also permits designing different constructive structures, depending on the customer requirements, starting from the same basic components – the modules. In the case of our design, the modules are the walls, the floor and the ceiling, identic as shape, but different as finishing, depending on their functionality. A modular building, unlike a structure *built on-site*, should be *assembled on-site*. This results in numerous advantages, both for the customer and contractor.

The main objective of this paper is to present a solution for a locking system for our modular building design. These small units called modules, should be kept together using a simple, reliable locking system. It should be hand-operated, requiring a limited driving force, and should compensate the dimensional errors.

2. MODULAR BUILDINGS

A modular building is a type of building that consists in the assembly of other smaller elements, often detachable and reusable, that are connected one to another in such a way to obtain a fully functional structure with many pre-established purposes. It often consists in a frame or support structure onto which other constituting elements are attached, either permanently or temporarily. It will not be confused with prefabricated constructions, in which fully designated spaces are fabricated in a factory, already assembled before shipping, and then sold as finite, fully functional, living or working spaces.

Modular buildings consist of “modules”, which are the constituting elements of the building. The modules can span from simple walls, to walls with functional elements inside them (windows, doors or electric grid and plumbing).

Their functionality could be either as temporary structures (hospitals, military camps, barracks, event buildings, disaster relief housings) or permanent structures such as offices or fully functional homes.

The modules are designed and fabricated with the intent of having a unitary design and functional language, they are envisioned to be assembled together therefore the engineering and design efforts are not only directed towards the best functionality of a single module but also to the assembly as a whole building, which is the core and meaning of a modular building. If the units wouldn’t be thought beforehand to be the constituting elements of a whole functioning assembly then the design of modular elements for building purposes would be pointless [1].

2.1 Existing solutions for modular buildings

The history of modular buildings is quite long, but one of the most significant moments in its evolution might be considered the Industrial Revolution, which came with new materials and new technologies, thus “revolutionary” solutions.

In 1851 the first World Exposition, at the time named "Great Exhibition of the Works of Industry of All Nations", was held in London. The Crystal Palace was an outstandingly huge structure built from cast iron beams and frames and plate-glass (Figure 1).

Figure 1 Chrystal Palace – drawing [5].

The structure was meant to be built quickly in order to accommodate the events of the Great Exhibition, but also be able to disassemble for relocation, being meant just as a temporary construction. The Crystal Palace is a perfect example of prefabrication and modularity used at their best capacities for the most unthinkable purposes, thus breaking the myth that all modular and prefabricated constructions look the same. Prefabrication meant for modularity gives enormous advantage in terms of design flexibility and the materials involved. Up to this day, the Crystal Palace still remains one of the main examples of peak technical capabilities, culmination of a period of technological evolution [5].

Modular and prefabricated construction found its use in war applications as well, even if not in the direct meaning of it. Prefabricated constructions became increasingly common in the battle field due to their reduced cost, ease to transport and build. Infirmaries and mess halls provided great support to fighting troops, such as in the Crimean War, in 1855, where prefab hospitals were first used. The Brunel's Renkioi hospital is seen as one of the first pioneers of prefabrication (Figure 2). The design of the hospitals was created by the architect Isambard Brunel, asked to develop a series of prefabricated hospital units to be deployed on the battlegrounds. Reportedly, the hospitals presented the possibility of being extended in order to accommodate from 500 to more than 1500 patients. They were designed to house every needed comfort possible while also remaining a very cheap and easily transportable solution [2].

Figure 2 Brunel's modular hospital [3].

After WW2 many countries remained deeply afflicted by the war. Britain received a great deal of damage after the war, to accommodate the families that lost their homes; therefore modular prefabricated houses were manufactured and deployed. In the US, many war veterans came back from war not being able to afford housing. This created a great effort into reducing the housing stress of the war veterans, consequently many projects were proposed. One of the most interesting and outstanding was the Dymaxion House, initially designed by the architect R. Buckminster Fuller in 1927 and then continued by the aviation company Beech Aircraft. The concept consisted of a circular shaped, aluminum covered house with a metal domed roof (Figure 3). It was meant to be built out of an aluminum frame and covered in aluminum plates riveted together, with other components made of stainless steel and plastic to be used. The construction, unsurprisingly, was similar to the manufacturing of aircrafts and the materials were surplus from the WW2 technological effort [6]. The house was designed to withstand heavy weather and even tornadoes.

Figure 3 The original Dymaxion house [6].

Contemporary design comes with modern solutions, reflecting the new fashionable materials and styles, adapted to the people needs. Coodo is an example of prefabricated module designed to be used as a living space, working space, or for event hosting. The company, originated in London UK, offers a series of prefabricated modules suitable for different activities, focusing on a clean design language and simple, intuitive forms (Figure 4) [7].

Figure 4 COODO prefabricated modular house [7].

Most of the times, prefabrication has been the solution to economical scarcity, given the fact that the materials and techniques involved in prefabricating construction elements were (and still are) many times cheaper than acquiring materials for the on-site constructions. The cost is not reflected only in the manufacturing stage, but rather on the maintenance of the structure and the option one has when making use of it or when it cannot be used any longer. Moreover, the building time also influenced the decision of whether or not to use prefabricated modules as a construction alternative. Being able to quickly erect houses, one of the primaries needs of human beings, in a ground breaking time span is probably, alone, enough to make one choose using prefabrication as their preferred construction solution. The possibility to move out "with the house", instead of "from the house", might be an extra bonus.

2.2 Interlocking Systems

When designing a modular construction, or a modular house in particular, some specific issues might occur, like the way the modules are assembled. Designing such a system becomes more complex as the requirements are various and sometimes tough. When assembling the parts of the modular house, the parts might not be identical, having different modules for floor, walls, or ceiling, like in our design [4], [8]. However, the locking system should be universal, fitting to all modules combinations.

Considering the advantages of the modular constructions, previously presented, the locking system should provide the same qualities, like fast and ease of assembly and disassembly, reliability, reduced cost, etc. Moreover, the system should provide the necessary force to keep together the panels and ensure a perfect insulation of the enclosure. It also should permit dimensional changes determined by fabrication errors or expansion caused by the weather. The locking solution should be universal, meaning that it could be used for all the modules of the building, if they are not identical or require intermediary connecting units, like in our case.

3. SEARCHING FOR THE IDEAS

Modular solutions are a response to green building demands. One of the main issues connected to buildings is their environmental impact and the little available end-of-life options for out-of-use buildings. Modular prefabricated buildings try to solve these issues by offering lower environmental impact building techniques and materials, as well as a broader end-of-life option spectrum for the products.

For these reasons, our modular house solution involves a two level modular concept. The first level is represented by the "panel entity" and contains several similar square modules: wall with window(s), wall with door, ceiling, floor and connectors. These modules can be assembled according to the building intention, more precisely, according to the space purpose: bathroom, living room, bedroom, etc (Figure 5) [8].

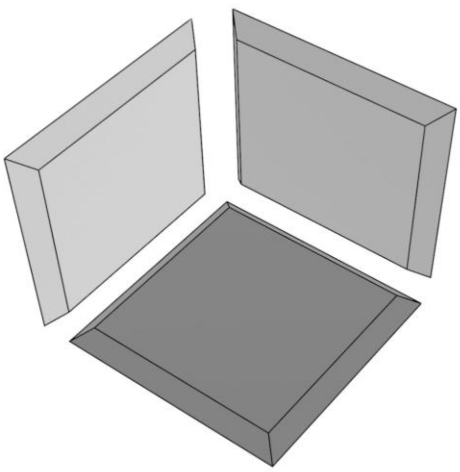


Figure 5 The modular panels assembling.

Assembling the functional units/modules should result into a complex construction like the one presented in Figure 6.

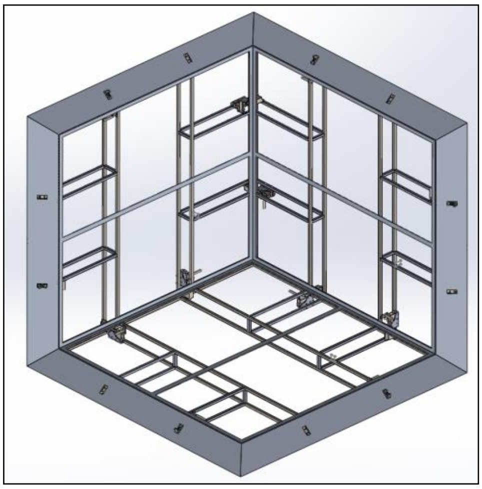


Figure 6 A modular partial "cube" built from flat panels.

The second level is the "volume entity", which allows the house surface variations by juxtaposition of several "cubes". This depends also on the house structure and each space aria. As an example of the capabilities of such design, Figure 7 shows an example of possible configuration.

Most of the existing solutions for fixing the modules are universal ones, like bolts and nuts, either they are first, or second level modular constructions. The research on locking systems did not reveal dedicated solutions.

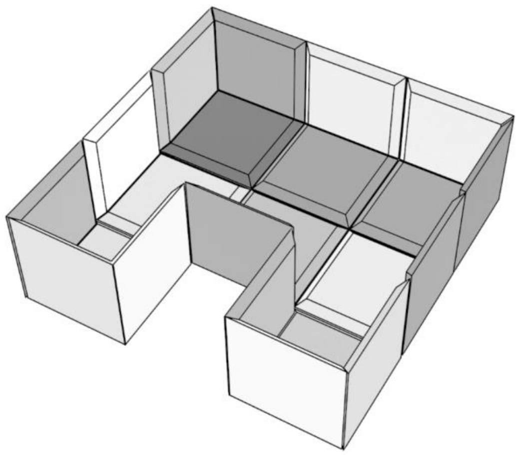


Figure 7 Example of modular "cubes" assembly.

This also puts a greater focus on the design of an interlocking system that should assure the continuous and functional connection between each element whilst still maintaining a modular and, possibly, mobile and non – destructive assembly solution.

The modular construction solution is imposing a number of restraints which come as supplementary constraints for the locking system design. The identified restraints are presented as follows.

The locking system should connect the square faces having contact under a 45^0 angle. It should consist of two parts: the active mechanism which should be placed inside one panel, and the passive part (the socket) which should be placed inside the adjacent panel. The socket volume should be limited for permitting even the assembling of one panel with a connector [8].

The assembling solution should provide a wedging force necessary to keep the parts together.

Given the assembling conditions, some ideas were generated in order to solve the problem and respecting all the requirements previously presented. The sketches of these ideas are shown in Figure 8.

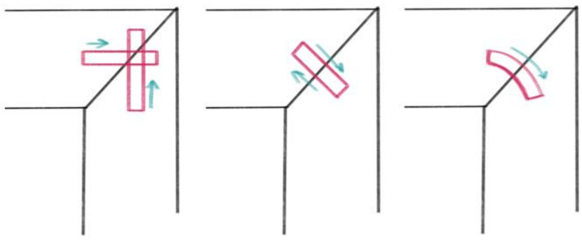


Figure 8 Variants of locking systems

All variants involve one or two sliding elements actioned from one side and sliding into the opposed one into a specially designed slot. The sliding element could be straight or curved. Variant 3 (Figure 8, on the right side) was preferred, because it fulfils better the sealing requirement given the conditions of compensating the differences in dimensions determined by fabrication or assembling errors. It also provides the wedging force necessary to keep the panels in contact.

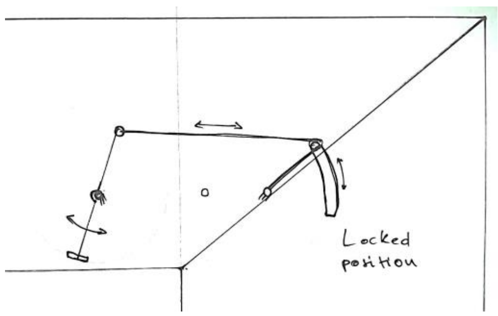


Figure 9 Locking mechanism, principle sketch.

The sketch in Figure 8 helped dimensioning the elements according to the existing space (the width of the modular panels). It also was useful for the lay-out design e.g. calculating the angles and the dynamic dimensions of the mechanism, for establishing the overall dimensions of the ensemble, given the moving parts of it.

The design of the locking mechanism was based on a preliminary kinematic synthesis that was meant to determine the range of motion for the mechanism and dimensional dependences between elements and the motions to be accomplished (Figure 9).

This stage continued with a primary evaluation of the necessary force for this mechanism manual driving. This resulted into a primary evaluation of the forces that will stress the mechanism parts.

Starting from the primary sketch, the design process continued with creating a basic construction 3D model using specific dedicated software.

The restraints impose limitations in overall dimensions of the mechanism and consequently for all the components; also limitations in angular displacements occur. The requirement was for the mechanism to be hand operated. For this reason, the chosen design solution required an angular displacement of the handle, and a multiple linkage system to amplify the force [2]. Once the mechanism is activated and set up closed, it is necessary to hold on position. For this reason, the proposed solution should include a ratchet.

3. MECHANISM DESIGN

The locking mechanism has been designed as a linkage mechanism composed of 3 main functional bodies or 3 bars. The mechanism has 3 arms, the first one and the last one pivoting on fixed ground rotational joints, as can be seen in Figure 10.

The main components are as follows: a driving arm (1), linkage bars (2) and the latching bolt (3). The joints are rotational joints, A, B, C, D. Only joint B and E are fixed to the ground, therefore joints A, C rotate around joint B, while joint D rotates around joint E.

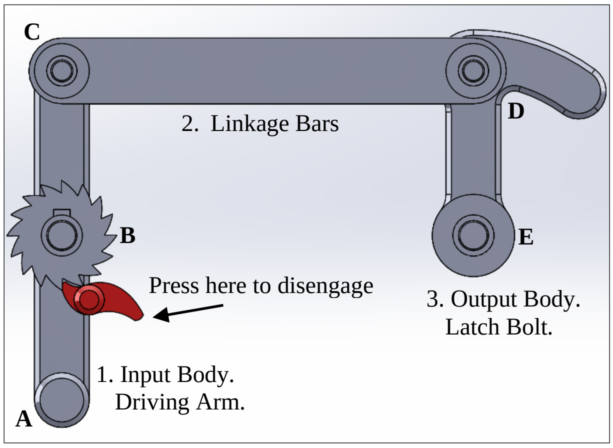


Figure 10 Locking mechanism components.

On joint B, a ratchet mechanism is located, with the ratchet in red, also used for blocking the mechanism at a certain angular position of the locking wheel around joint E (displacement angle ~ 45^0).

The ratchet is disengaged by pressing on the ratchet tooth opposite side as shown in Fig. 10. The ratchet tooth contains a spring inside, which ensures the component is pressing onto the ratchet's wheel at all times (Figure 11).

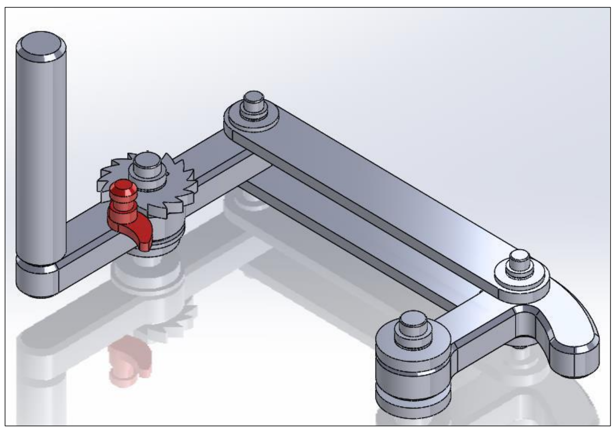


Figure 11 Locking mechanism, isometric view.

The ratchet can be hand-operated from the exterior, by the person responsible with the panels assembling. The mechanism is driven by pushing the "Input Body" (Position 1 in Figure 10) and the "Output Body" (Position 3 in Figure 10) is moving consequently.

A case for the mechanism has been designed in order to contain the moving parts and also provide the ground element for the fixed components. The case consists of an upper and lower steel plate covers that act as supports for the mechanism. Joints B and E are fixed in the holes shown in Figure 12. A slot has also been designed to guide the link bars of the mechanism, namely joint C, which will be inserted in the slot during assembling and will move along its path according to the trajectory that has been calculated for the moving parts of the mechanism.

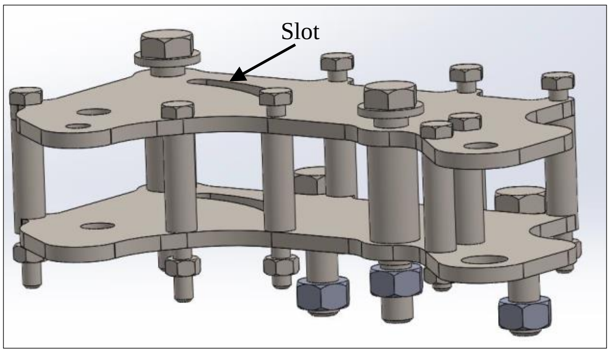


Figure 12 Mechanism case.

Next, the mechanism should be inserted into the case, and the resulted ensemble is presented in Figure 13. This can be assembled separately with the specific adjustments made "outside". Also, this can be considered as part (a whole) or spare part in the assembling-disassembling process.

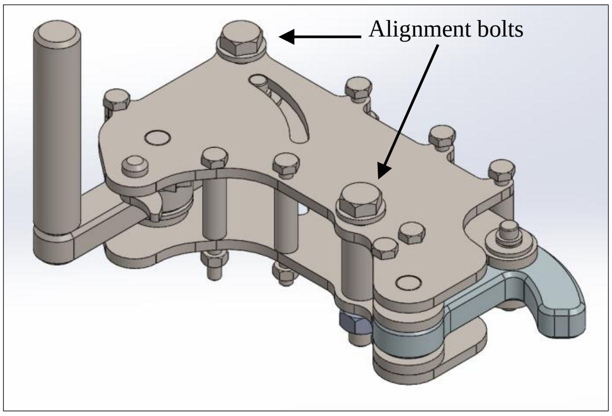


Figure 13 Assembled mechanism.

Two bolts with higher diameter also fulfil the alignment function (see Figure 13), meaning that in case of disassembling for repairing reasons, or for replacing worn-out components, the re-assembling process will lead to exact the same alignment of the whole.

In addition to the containing case for the mechanism, an extra "glove" has been designed, in order to fix the whole mechanism to the main modular panel assembly. The fixing case can be seen below, in Figure 14.

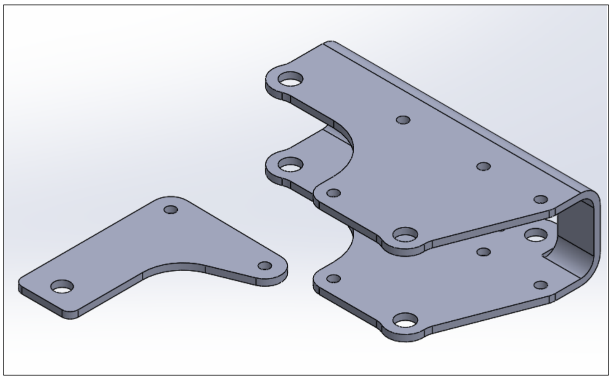


Figure 14 Frame fixing case.

This case is mounted into the modular panel and helps the locking mechanism assembling. It should not be disassembled from the building modules, unless they must be repaired or replaced. Figure 15 shows the system mounted inside the case, and Figure 16 presents the entire ensemble mounted on the building module.

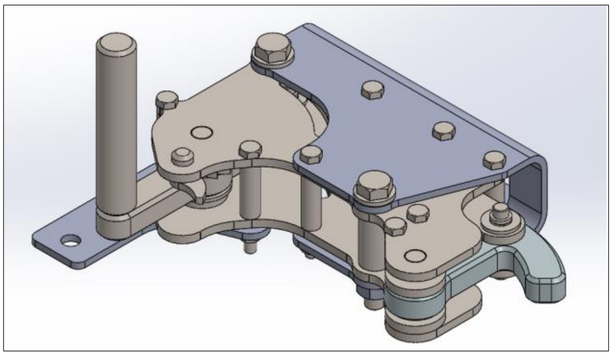


Figure 15 Assembled mechanism into the frame fixing case.

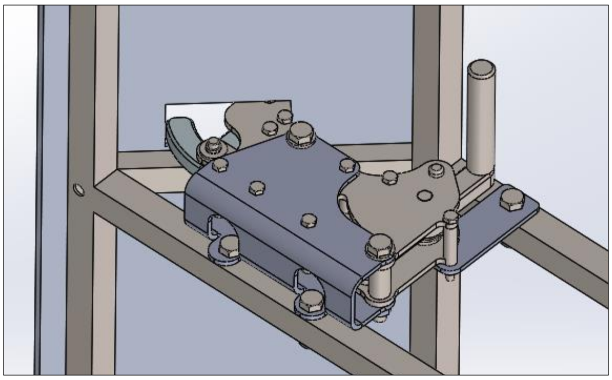


Figure 16 Mechanism as sub-assembly mounted on site into the frame fixing case.

A strike has also been designed for the locking mechanism. A strike is a common component in locking mechanisms, it is the "receiver" part of the mechanism, meaning the area or component into which the latch bolt or the dead bolt slide inside to accomplish the locking state of the mechanism. In the context of this paper, the strike is the receiver located inside the panel onto which another panel is latching on. As such, it has to ensure the proper fitting of the latch bolt, based on the previously studied kinematic analyses for the displacement of the latch bolt from one module to the other. In Figure 17 can be seen an easy and effective solution for a strike.

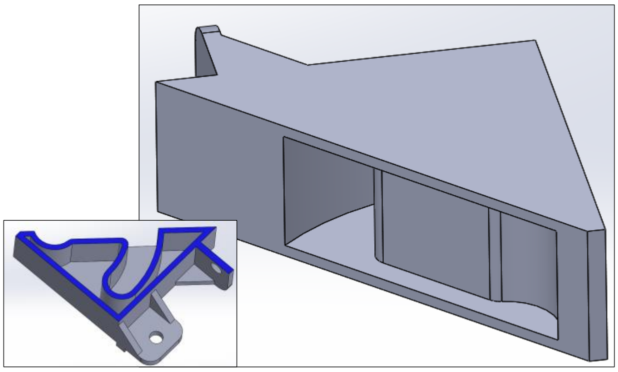
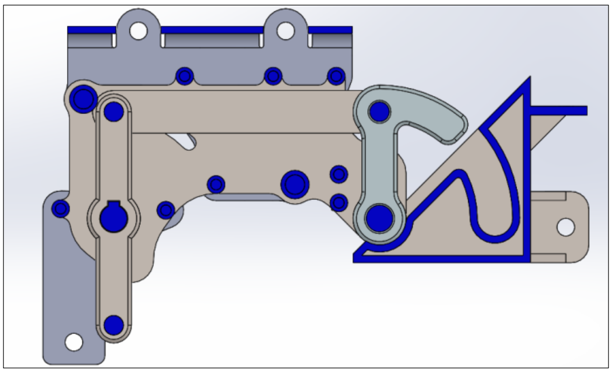
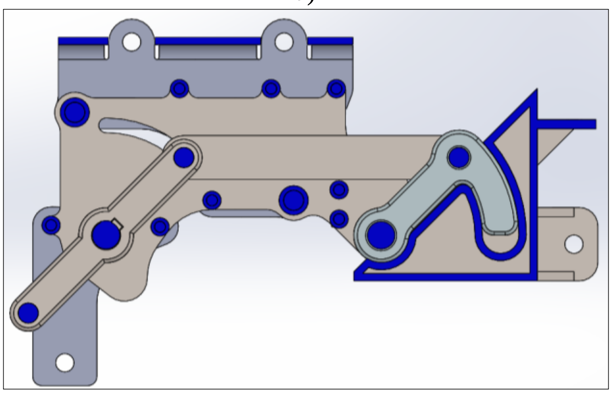


Figure 17 Strike component of the locking mechanism ensemble (section view in the detail)

In Figure 18 can be seen the two states of the locking mechanism ensemble, including the strike. The components have been placed as they would be in the final assembly in which they fit in the designated areas in the modules.



a)



b)

Figure 18 Unlocked and locked state of the complete mechanism.

The ratchet has been designed to lock the mechanism at 44^0, this ''under - locking'' feature having the purpose of compensating dimensional deviations, misalignments, internal and external forces at the contacts of the modules interlocked, as well as providing the necessary compression of the sealing gaskets between modules.

Additionally, to overcome possible torques that may appear at the locking of the mechanism, a lever wrench has also been designed as a replacement for the handle of the locking mechanism.

4. CONCLUSIONS

Modular buildings represent an old solution, but with modern ways of problem solving. The advantages of modules are obvious, the possibility of simple and fast assembling and disassembling process represent only one example of them. For fulfilling such goals, a proper inter-modular locking system is necessary, able to ensure all the qualities required for such a device.

The solution described in this paper based on a hand operated linkage mechanism, is simple, reliable, easy to operate and maintain. Also, it is universal, permitting the connection of all modules necessary for obtaining the entire structure of a building.

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