

Author's post-print: M. Alonso Martínez, J. J. del Coz Díaz, D. Castro-Fresno, A. Navarro Manso. "New mechanism for continuous and bidirectional displacement of heavy structures: design and analysis". *Automation in Construction* 44 (2014) 47–55.
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New mechanism for continuous and bidirectional displacement of heavy structures: design and analysis.

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Abstract

The aim of this paper is to design and study a new mechanism for moving heavy structures using the force of friction. The mechanism designed is called DCACLM and was patented in 2011. This new device is based on an inverted crawler which is able to displace heavy structures such as large span bridges in a continuous and bidirectional way. Furthermore, the DCACLM design has taken into account other important aspects such as safety and sustainability in order to develop new construction methods. Nonlinear numerical models using the Finite Element Method have been developed to study the complex structural behavior of this new mechanism. The main conclusions provide acceptable results in terms of stresses and strains for the main elements of DCACLM.

Keywords: Non-linear FEM analysis; non-linear contact models; launching bridges machines; heavy structure displacement; mechanical design; building operations safety.

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1 Introduction

Erection is a common operation in many bridge constructions but it is also one of the most dangerous phases. Most accidents take place during this stage as is indicated in previous studies [1]. The main reasons for these collapses, without considering natural catastrophes, are human error in the design of the bridge or during its construction. It has been proved that if the bridge structure is able to resist its erection stage, it will work well during its service life [2]. Other authors [2], have studied the importance of reliability and safety in the temporary procedures, such as the erection phase. In this sense, two main aspects have to be taken into account to ensure safety during the erection procedure. The first is the time of exposure to environmental loads or operational effects. The second one is the cost increase due to the temporary equipment used in the construction.

In order to automate the main operations on large constructions, such as launching bridges, different procedures have been developed. Hydraulic jacks are commonly used to lift or erect heavy structures. New devices have been designed for specific constructions, such as the Shanghai Grand Theater, which was built in 1994 [3]. Other systems have been used to move heavy structures: the use of synchronized jacks in Denmark, [4]; the introduction of transducers and software for real-time control in 1992, [5]; the Beijing West Railway Station construction where 24 hydraulic jacks were needed, [6]. Other important contributions to improve efficiency and safety of hydraulic jack operations include the electrohydraulic system developed recently by Zhinan Mi *et al.* [7]. In that paper, an electrohydraulic system was designed to reduce the difficulties in using hydraulic jacks to carry out the consecutive displacement of lifting and lowering. This system avoided dead times caused by starting and stopping of the jacks, and it can be applied in many construction fields where erection, lifting or displacement of heavy structures is needed.

Although the global economic crisis has impeded new construction evolution, the construction industry is still working in one direction: the improvement of methods taking into account safety and sustainability. In this sense, construction trends include the following:

- Large span bridges which reduce the number of piles and the temporary equipment during the construction procedure.
- Development of new systems which allow consecutive movement of large structures, that is, lifting and lowering for vertical displacements or forward and backward movements for horizontal displacements.
- Safety improvement in construction procedures due to important accidents which have occurred due to human errors or other factors. Safety risks must be reduced and avoided as much as possible.
- Currently, environmental considerations and sustainability in construction methods are an important consideration in this field.

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This paper presents a new system to displace heavy structures. The main application of this system is focused on launching bridges. According to previous studies, the tendency in bridge construction is to design new mechanisms which decrease the operation time, safety risks and improve the quality of the procedure [8]. Novel ideas in bridge erection machines were presented by Rosignoli, where the importance of the relationship among the launching mechanism, human decisions and structural design is remarked.

In this research, a new mechanism for continuous launching displacement is explained in several sections. The design, the tridimensional models and the overall dimensions are presented before the description of the working principle. Then, numerical studies of the new design are presented. In this sense, the geometrical design of the new mechanism is completed with nonlinear numerical analysis by Finite Element Methods (FEM). This methodology has been widely used to solve nonlinear problems in different fields and topic. Many other FEM-based studies have been developed in engineering, [9]-[10]. The conclusions of this paper reveal a new device which is able to move heavy structures in a bidirectional and continuous way. Although the new system can be used for other applications, this study is focused on launching bridges, mainly by means of the Incremental Launching Method (ILM). In this sense, the mechanism designed makes an important contribution to this construction methodology improving efficiency of the ILM, decreasing safety risks of the current operations and taking into account sustainability in civil engineering.

2 New mechanism for displacement of structures

Taking into account the main application of the new mechanism designed in this paper, the review of similar systems focuses on systems for launching bridges. The main devices currently used in the ILM have been reviewed.

The most common systems used for launching bridges are launching jacks and tow systems using bars or cables. [8]-[11]. Both of these systems work with hydraulic jacks which provide important advantages for displacement of heavy structures. However, this kind of equipment has some important disadvantages that the construction industry wants to solve, [12]. The main problems presented by the current systems for bridge launching are the following:

- The systems need auxiliary equipment to control the load on the bridge structure during the launching procedure in order to avoid its collapse. It is well known that the maximum loads on the bridge structure occur during the launching process [1], [13]-[15]. For this reason, the most serious accidents have occurred during the bridge erection when it is very important to ensure safety during launching to avoid material and human damage.
- The systems are not continuous; there are dead times due to retraction of hydraulic jacks rendering the consecutive displacement (forward and backward) of the bridge structure

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impossible. Currently, backward displacement is difficult: it is necessary to stop the launching, support the bridge and use many auxiliary systems to carry out this operation. In this sense, the cost and time of the construction is increased.

- Current systems cannot be used for bridge structures made of different kinds of materials or geometries.
- Due to the highest risks that are presented during the launching procedure, the efficiency of the systems should be improved in order to reduce the time of the bridge displacement. The efficiency can be increased using faster mechanisms and decreasing the dead times.
- Environmental protection during building started to be considered a few years ago. Presently, the environmental measures and the development of sustainable practices are very important for the construction industry. In this context, the existing systems are usually not reusable or recyclable for other operations. Furthermore, basic operation in civil construction did not consider environmental damage. Fortunately, social interest in environmental conservation has led to the design of new construction procedures.

The authors of this research paper have been working in this topic for years. The design of new bridge construction methods and the improvement of the current disadvantages are an important research line. In this sense, two international patents have been developed to study new methods for launching heavy structures [16]-[17]: a new method for launching bridges based on self-supporting double decks and a new device for continuous displacement of heavy structures.

The new method for launching bridges is able to push steel bridge structures of 150 m. length reducing the auxiliary equipment due to the double height of the deck during the launching process. Two decks are moved jointly in order to increase the load capacity of the critical section during the launching procedure. In this way, the patch loading resistance is improved and the deflection of the structures is reduced. Furthermore, this new system is more efficient, safer and more sustainable than the current ones. This new methodology is an important contribution to engineering in the construction field and was patented in 2012, [16].

The new device for continuous displacement of heavy structures enables the displacement of structures of up to $7.5 \cdot 10^6$ N vertical live load. This new mechanism was patented [17], and is described in this research paper. This new device is based on an inverted crawler which is able to move heavy structures in a continuous and bidirectional way. Furthermore, the new mechanism adds safety systems to the launching procedures and it can control the load in real time during the launching procedure. The mechanism designed for continuous displacement of structures is named DCA CLM (DCA Continuous Launching Mechanism).

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2.1 Description of the mechanism

The mechanism presented in this paper works as an inverted crawler. Two motors move the gears which displace a couple of transmission chains. The transmission chains transmit the horizontal force which moves the bridge structure. The structure is supported by a non conventional chain called, a support chain. The support links have a plate of elastomer at the top to displace the structure by means of the force of friction. These sheets can be changed depending on the material of the structure which is moved. The links of the chains are joined by bolts which have rollers in order to follow two rails. In Fig.1, the main elements of the DCACLM are shown.

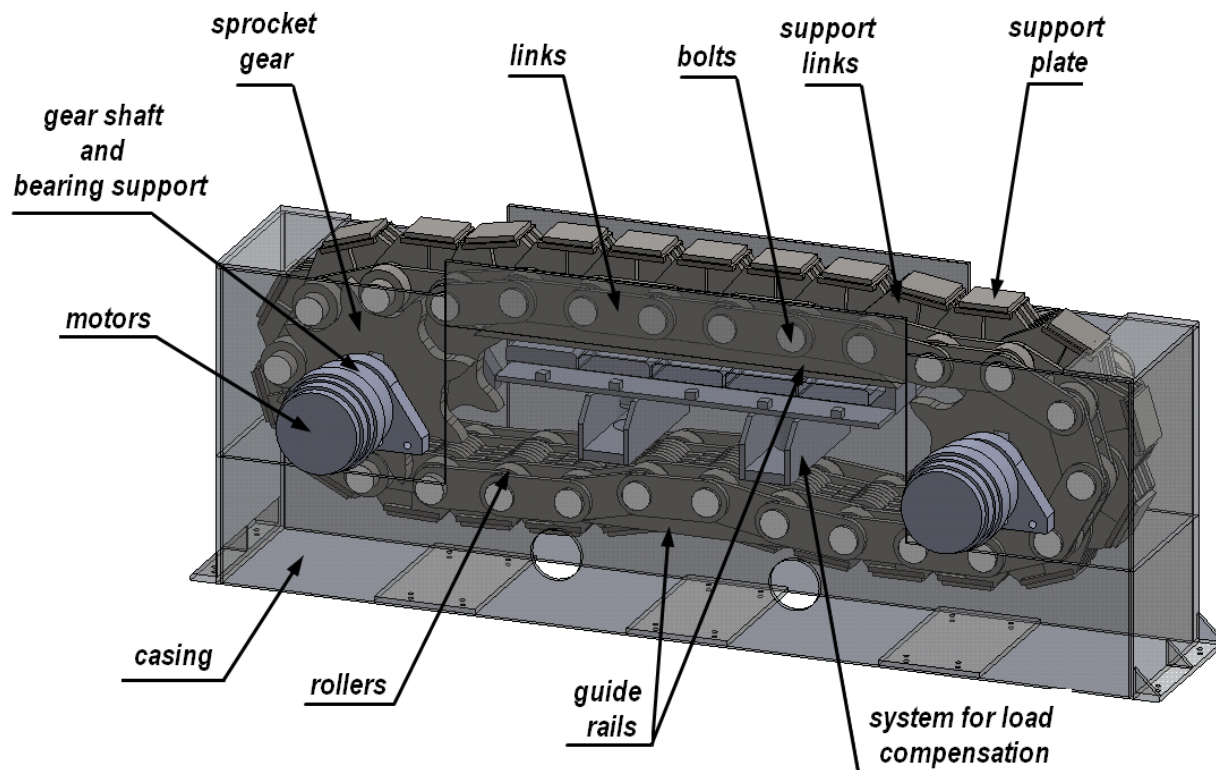


Fig.1. Main elements of the DCACLM.

One of the most important innovations of the DCACLM is the system for load compensation, shown in Fig.2. This system is able to control the normal load over the mechanism during the launching process as well as to adjust the support links to the deformed shape of the structure at all times. The system for load compensation is also a safety system because it can stop the launching process if overloads are detected.

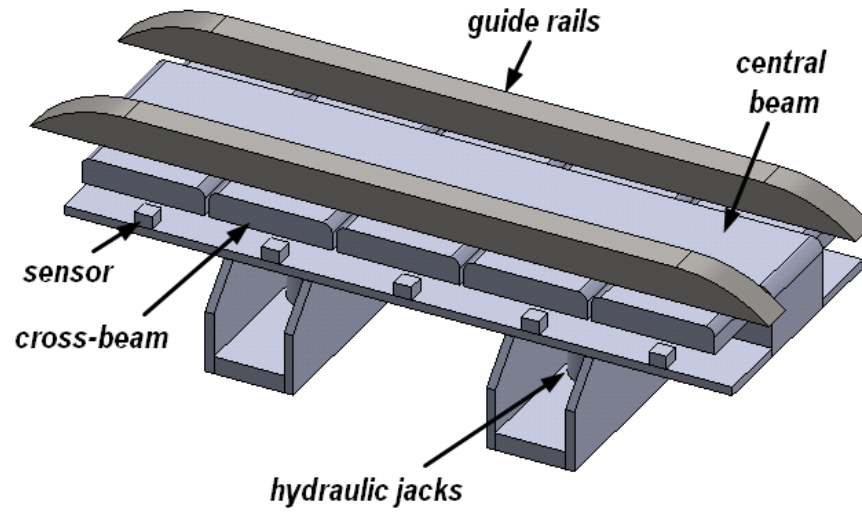


Fig.2. System for load compensation

The rollers of the transmission chain are supported on the guide rails which are placed over the cross-beams. These cross-beams enable the vertical displacement of the rollers making it possible to adapt the support links to the shape of the bridge, which is an important contribution. During the launching process the steel structure of the bridge is deformed and the contact between the structure and the launching device can be inadequate. In fact, if the structure loses contact with the support surface it could collapse or stop the displacement. Thus, an important problem in the launching procedure currently is to ensure contact between the bridge structure and the launching jacks. DCACLM makes this possible by means of the system for load compensation. In this paper, the structural behavior of this system is studied numerically in order to obtain the cross-beams' deformation when high normal loads are applied.

In this research paper the tridimensional and parametric model of the DCACLM is presented, as well as the numerical study of the main elements and assemblies.

3 DCACLM design

The design of the DCACLM has been carried out using advanced simulation tools: Computer Aided Design (CAD) tools for the geometrical models and Numerical Simulation by Finite Element Method (FEM) tools for the numerical studies, [18]-[19]. In this section, the geometrical model of the DCACLM and the numerical models developed using FEM are explained.

3.1 Geometrical model

The geometrical model of the DCACLM has been drawn using Computer Aided Design (CAD) tools in order to obtain a tridimensional, parametric model. The design of the DCACLM has taken into account a normal load of $7.5 \cdot 10^6$ N. so that, with a 0.5 value for the coefficient of friction, the

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force of friction or launching force can be about $3.75 \cdot 10^6$ N. The design of the mechanism assumes that two or more devices can work together or alone. Furthermore, following the tendency to reduce the environmental impact of civil works, the DCACLM has been designed as a modular and compact device, which is anchored to the terrain and can be used in other constructions easily.

Fig.3 shows the design sequence of the geometry of DCACLM. The main dimensions of the components have been calculated from the maximum normal load that the mechanism must support. Furthermore, the number of support links under the bridge structure is also important to ensure the displacement by means of the force of friction. In this sense, the main dimensions of the DCACLM were fixed and then, the rest of the components were assembled. In Fig.3, the main dimensions of the mechanism and the process of assembly is shown.

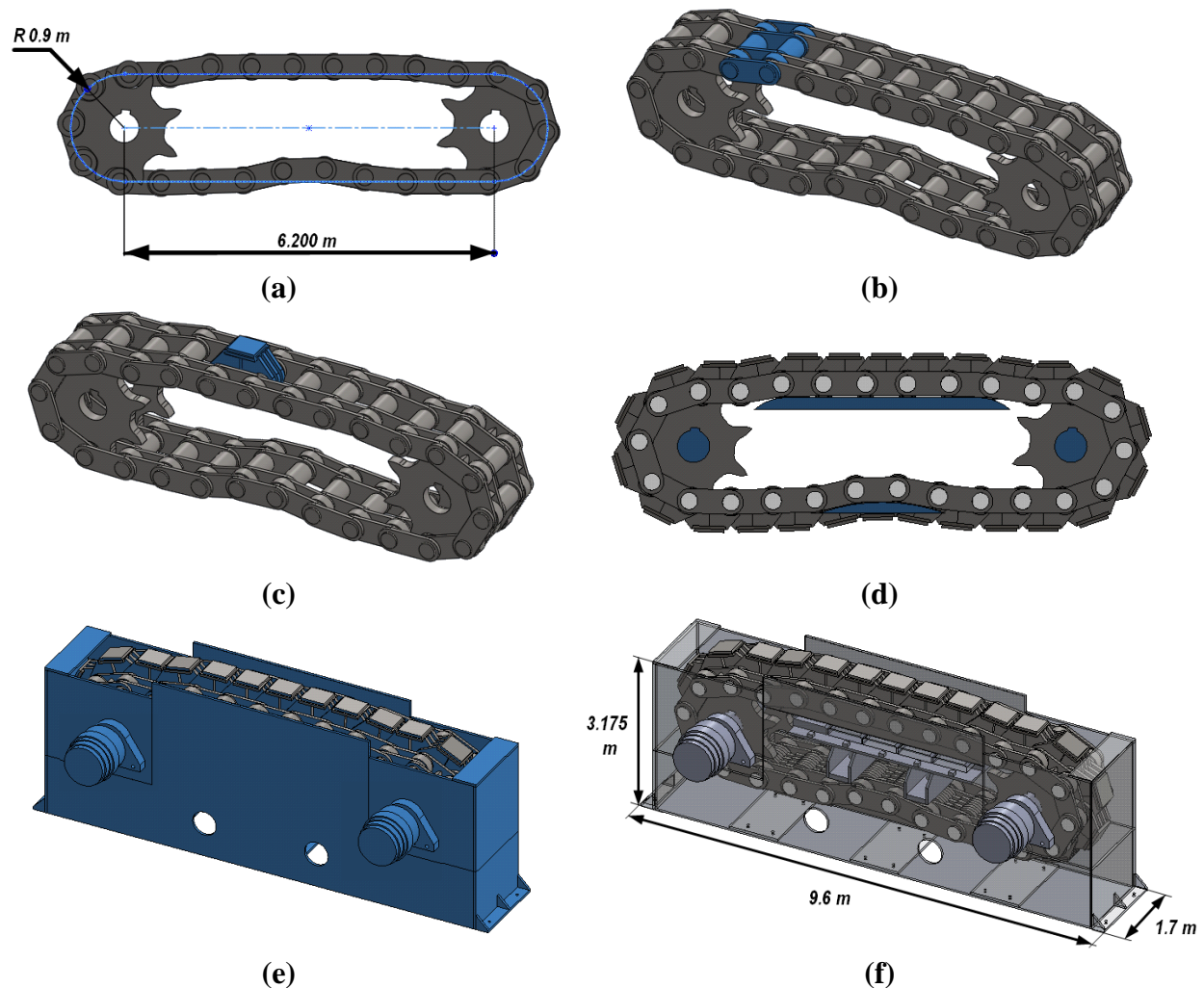


Fig.3. Design sequence of the geometrical model using CAD tools: (a) initial sketch of the chain; (b) transmission chain pattern; (c) support links; (d) guide rails and gear shafts; (e) casing and motors; (f) system for load compensation and general dimensions.

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The geometrical model is shown in Fig.3. Fig.3.(a) shows the sketch used to draw the chain considering the main parameters, the distance between the shafts and the diameter of the sprocket gear. These two values provide the chain pass and the most important dimensions of the links. Fig.3(b) and (c) show the assembly of the chains. Fig.3(d) adds the guide rails and the shafts of the gears which must resist high torque in operation.

3.2 *Numerical models for structural analysis*

The numerical model of the new mechanism has been developed using the Finite Element Method (FEM). In this way, the mechanism has been studied taking into account the non-linearity due to large deformation and the non-linear contacts between elements, [20]. These structural analyses are considered static problems due to the slow variations of the structural response. In this subsection, three different numerical models are explained:

- The chains in contact with the bridge structure, which must support the vertical and horizontal live loads.
- The sprocket gear, which has to support the torque of the motors.
- The system for load compensation, which has to support the maximum vertical live load, satisfying the serviceability limit state.

3.2.1 Sprocket gears

The sprocket gears have to be able to transmit the movement from the motors to the chains of the structure. Due to the high loads that they must transmit, their geometrical design has a special shape. The most important dimensions of the sprocket are the pitch diameter and the number of teeth, with which it is possible to obtain the pitch of the chain. Furthermore, the diameter of the rollers which engage with the sprocket is also important to ensure correct transmission.

An adequate movement in the mechanism depends on the geometry of these sprockets, so their design and dimensions have been standardized following national and international standards [21]-[22].

The geometry of the sprocket designed is shown in Fig.4(a) and the geometry is meshed by finite elements in Fig.4(b). The total numerical model consists of 32,492 nodes and 10,280 elements. The elements used for the solid part are SOLID186.[23]

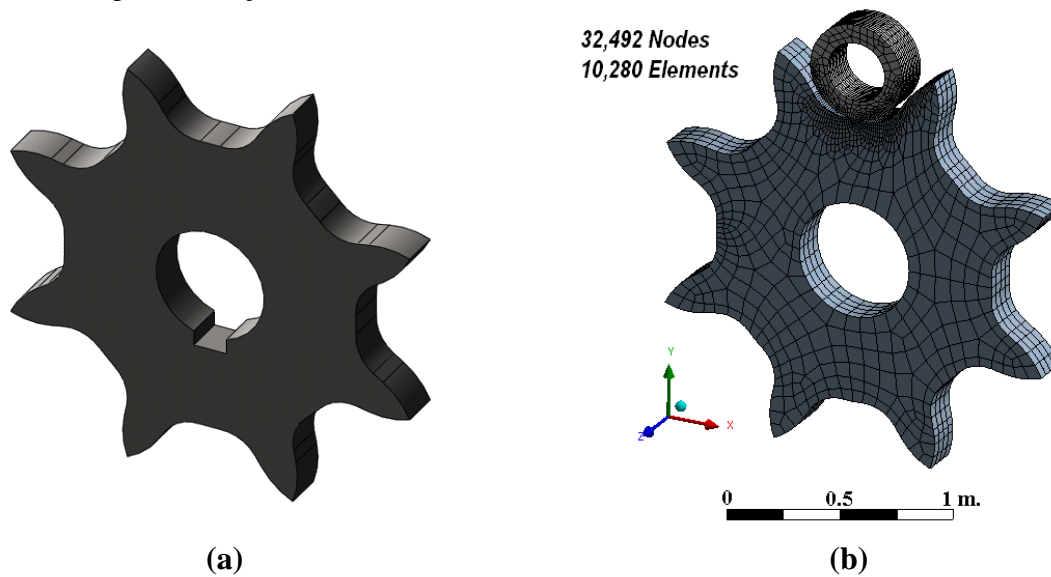


Fig.4. Geometrical model of the sprocket gears.

Due to the high torque that this element has to transmit, the stress in contact with the roller of the chain has been studied. The numerical model is a non-linear model due to the contact behavior. The numerical model studied is shown in Fig.5. In Fig.5(a), the boundary conditions of the problem are shown: the movement of the sprocket is prevented while the roller attempts to displace it horizontally. The contact surfaces are shown in Fig.5(b). The contact used was frictional, with a coefficient of friction of 0.1. The Augmented Lagrange Method was used as the algorithm for the frictional contacts. The elements used are the CONTA174 and the TARGE170, [23].

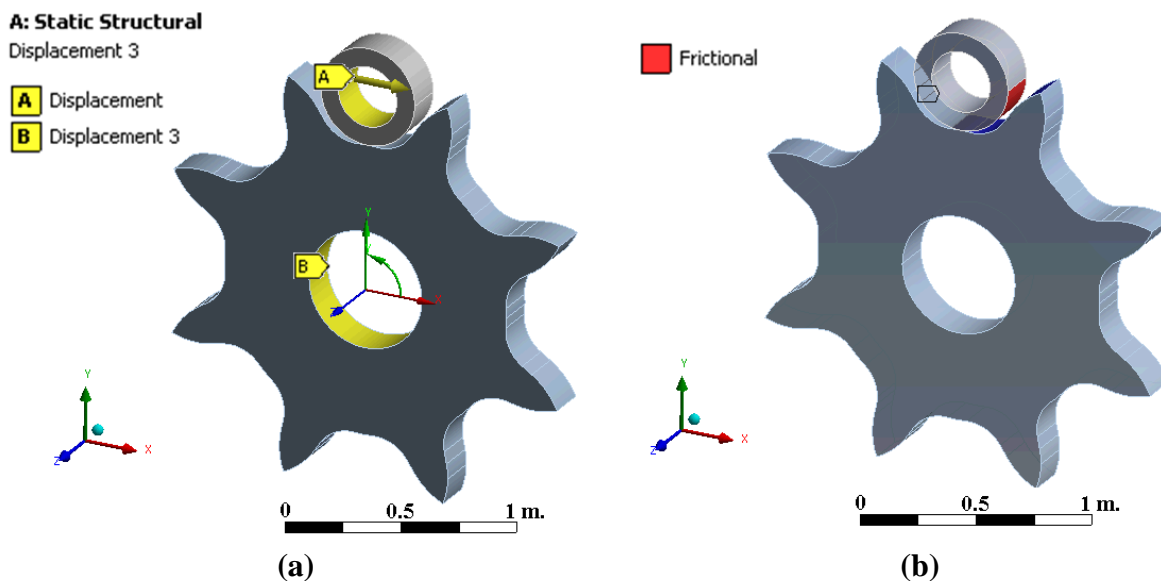


Fig.5. Numerical model of the sprocket gears in contact with a roller of the transmission chain: (a) boundary conditions; (b) contact surfaces.

3.2.2 Structural analysis of the chains

The chains are one of the most important elements of the DCACLM due to the high loads that they have to support. In this sense, the most loaded part of the chain is at the top of the mechanism where the structure is supported. The DCACLM design considers that the structure is supported by a minimum of four support links, taking into account that horizontal and normal loads are applied. Fig.6. shows the numerical model of the chains, while Fig.6(a) is the geometrical model, and Fig.6(b) shows the finite element mesh where several kinds of elements have been used: SOLID186, SOLID187, SHELL181 and SURF154 [23]. The total model is composed of 690,134 nodes and 412,388 elements.

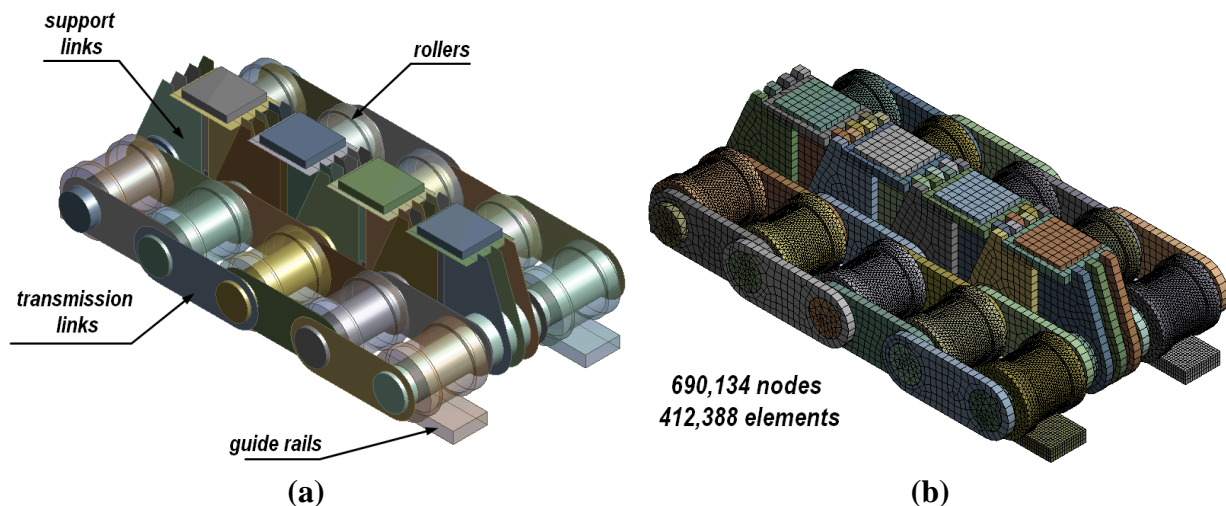


Fig.6. Numerical model of the chains: (a) geometrical model; (b) finite element model.

The boundary conditions of this numerical model are shown in Fig.7. On the one hand, the fixed support which prevents the vertical displacement of the chains, and on the other hand, the applied loads which are the pressure and the horizontal displacement. The normal pressure is equivalent to the maximum normal load applied for the structure, while the horizontal displacement is equivalent to the transmission force due to the torque of the motors.

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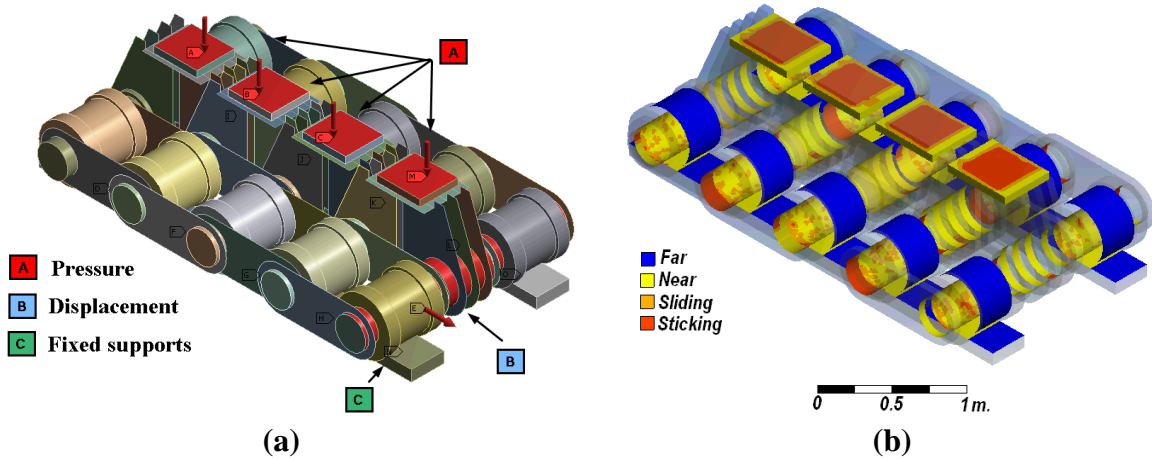


Fig.7. Numerical model of the chains: (a) boundary conditions and loads; (b) initial status of the contacts.

In Table 1, the characteristics of the non-linear contacts are explained. Two kinds of contacts have been used: bonded contacts which are linear contacts and frictional contacts which are non-linear contacts whose coefficient of friction is 0.1. The elements which are in contact must be treated specifically, so the mesh of these bodies has to be reduced in order to facilitate the convergence of the problem as well as to ensure reliable results. The problem has been solved using the Augmented Lagrange Method as the contact algorithm. The elements used for the contact elements were TARGE170 and CONTA174 or CONTA175, [23].

Table 1. Characteristics of the non-linear contacts in the chain analysis.

<i>Name</i>	<i>Elements in contact</i>	<i>Type of contact</i>	<i>Value</i>
A	Transmission link to bolt	Frictional	Coefficient of friction: 0.1
A'	Transmission link to bolt	Bonded	
B	Support link to bolt	Frictional	Coefficient of friction: 0.1
C	Support link to elastomer plate	Bonded	
D	Roller to bolt	Frictional	Coefficient of friction: 0.1
E	Roller to guide rail	Frictional	Coefficient of friction: 0.1

3.2.3 System for load compensation

An important contribution of the new mechanism is the system for load compensation which is able to control the normal load on the support links. This is very important for several reasons. It can adjust the support links to the deformed shape of the structure during movement and can add

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a safety system which detects overloads and stops the process avoiding the collapse or irreversible damage to the structure. To achieve this, a structural analysis was done by FEM to study the response of this system. The details of the geometrical model and finite element mesh used are shown in Fig.8. The elements used were SOLID186, SOLID 187 and SURF156, [23] for the geometry, and CONTA174 and TARGE170 for the contacts.

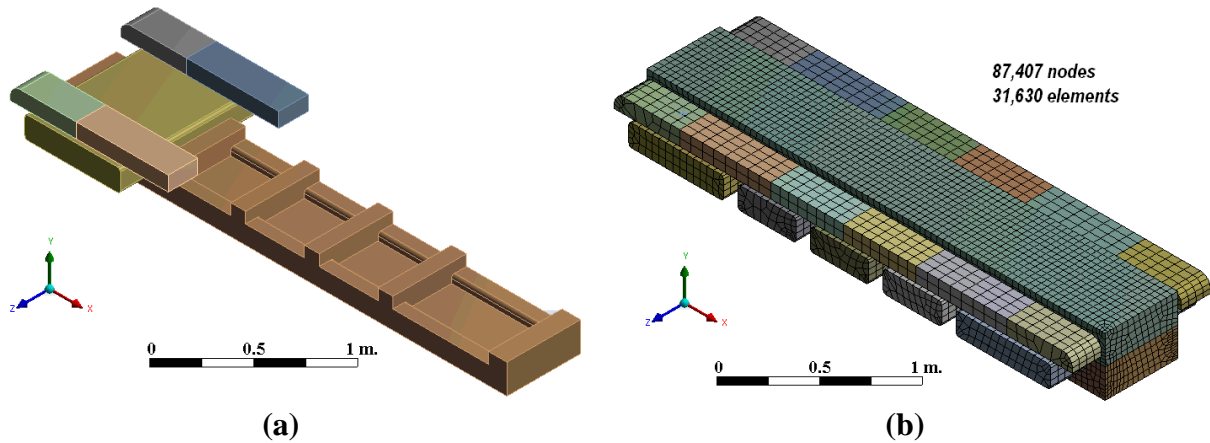


Fig.8. System for load compensations: (a) details of the geometrical model; (b) finite element mesh.

In this numerical model the reactions obtained in the structural analysis of the chain were used as input loads. The loads transmitted from the support links to the rollers are supported by the guide rails. These elements are flexible in order to enable adaptation of the support links to the shape of the structure by means of small vertical displacements. These displacements are controlled by the bending of the cross-beams. Special sensors under each cross-beam check in real time these displacements and order the stop of the movement. This system is supported by fixed circular areas equal to the contact surface of two hydraulic jacks which are able to apply vertical force. The numerical simulation of this system is shown in Fig.9.

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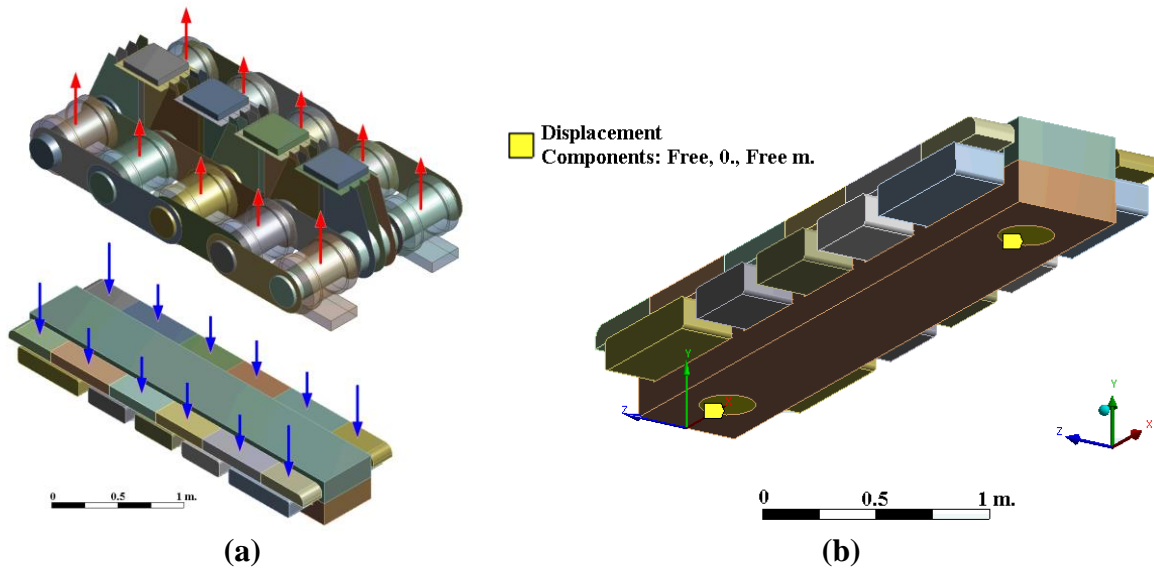


Fig.9. Numerical model of the system for load compensation: (a) applied loads; (b) boundary conditions.

4 Numerical studies

The numerical results obtained from the structural studies by FEM are presented in this section. The results are divided into three sub-sections: firstly, the results from the sprocket gear analysis, secondly, the results from the chains and, finally, the results from the load compensation system study.

4.1 Sprocket gear results

The results obtained in the numerical model of the sprocket gear in contact with the roller led to acceptable values of stress for the materials studied. The maximum value of the equivalent von-Mises stress is around $5.36 \cdot 10^8$ Pa, which is less than the maximum acceptable value for this kind of steel. Furthermore, the result of the pressure in the contact was obtained. These results are shown in Fig.10.

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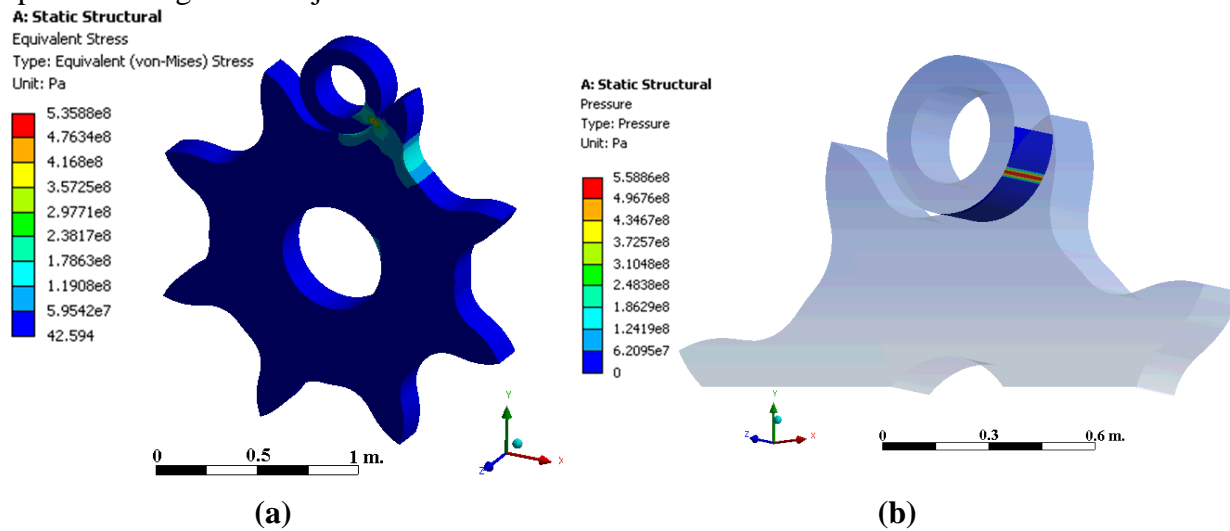


Fig.10. Numerical results of the non-linear analysis of the sprocket gear: (a) equivalent von-Mises stress; (b) pressure in the non-linear contact.

4.2 Chain analysis results

The results of the structural analysis of the chains, where high non-linear contacts are used, led to acceptable results from the stress and deformation point of view. In Fig.11 the results of the chains studied are represented.

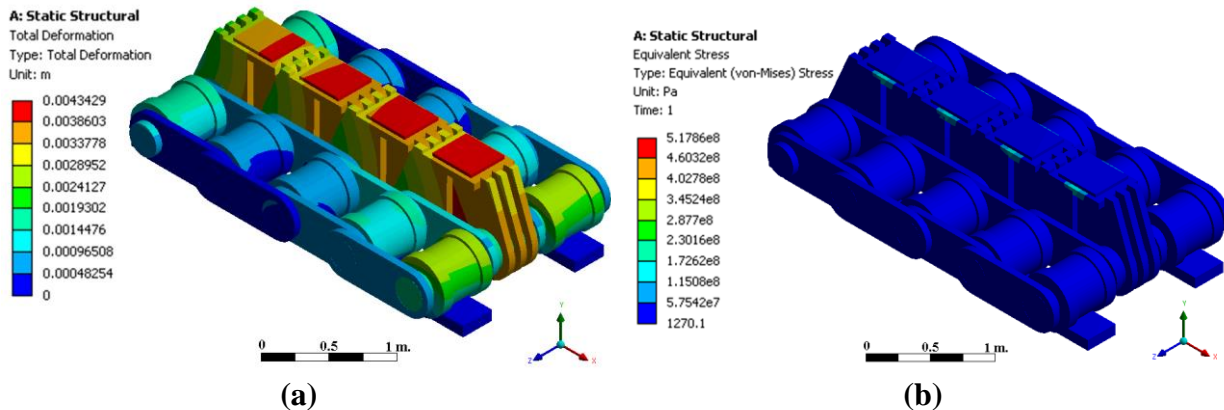


Fig.11. Structural analysis results of the chains: (a) total deformation; (b) equivalent von-Mises stress.

The maximum deformation of the chains was obtained at the top of the support links where the heavy structure is supported. This value is around $4 \cdot 10^{-3}$ m. Considering the stress state, the maximum values are on the rail guides due to the high reaction that these elements must support, shown in Fig.12(a). The maximum stress in these components is $5.17 \cdot 10^8$ Pa. Furthermore, the

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reaction force in each guide rail was obtained, shown in Fig.12(b). In this way, the force transmitted from the chains to the load compensation system was calculated.

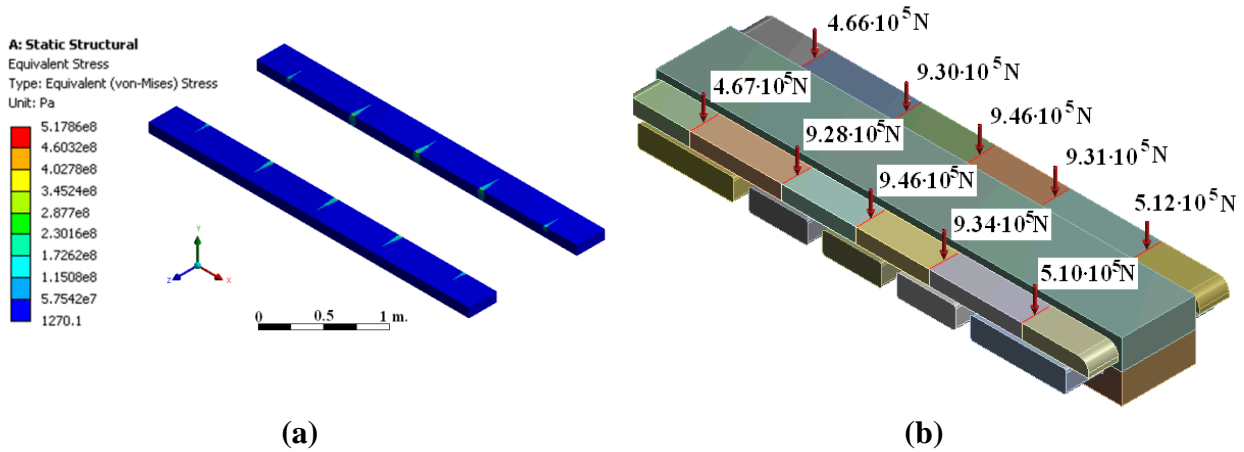


Fig.12. Equivalent von-Mises stress in the rail guide.

4.3 System for load compensation results

The results obtained in the system for load compensation analysis provide the total deformation of this system when high pressure is applied to the support links. The deformation of this system indicates the critical behavior of the mechanism. The maximum value of deformation obtained is around $4 \cdot 10^{-3}$ m. Furthermore, the analysis was completed with a stress analysis, where the safety factor was obtained taking into account the material properties. The results, shown in Fig.13, give safety factor values higher than 1, which means that the design is acceptable.

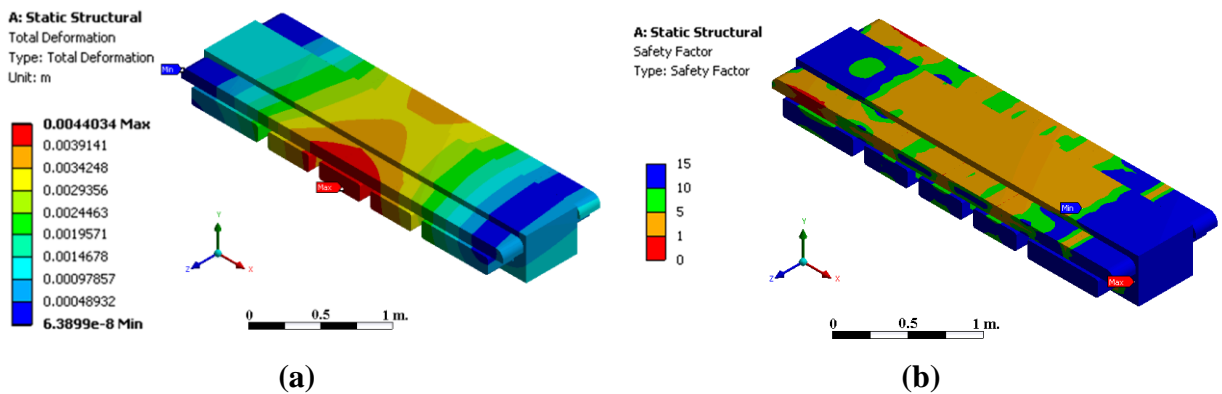


Fig.13. System for load compensation results: (a) total deformation results; (b) safety factor results.

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5 Conclusions

This paper presents a new mechanism, called DCACLM, for moving heavy structures by means of the force of friction. This new device was designed, studied and patented by the authors of this paper. DCACLM is based on an inverted crawler which, when fixed to the terrain, is able to support and displace heavy structures. The main elements of this mechanism were calculated in this paper by FEM using non-linear analysis. Firstly, the sprocket gears which deliver the force from the motors to the transmission chains were dimensioned, secondly, the chains composed of two transmission chains and a support chain were designed. Both chains are combined to support the efforts, the transmission chains support the horizontal stress, and the support chain resists the vertical load, finally, the system for load compensation, which is able to adjust the support links to the shape of the structure and detect overloads during the structure movement were developed. These three nonlinear analyses show how the elements are correctly designed in terms of stress and strain for the materials considered. DCACLM enables continuous and bidirectional displacement as the motors can move the chains in two directions, forward and backward. Furthermore, DCACLM supports heavy structures in a safe way because the load compensation system adapts the contact surface to the deformed shape of the structure and detects overloads that could give rise to the collapse of the structure. The main application of the DCACLM is launching large span bridges, for which high cost equipment is currently required and complicated and dangerous operations are carried out,[24]. In this context, the new device improves the efficiency of current systems and also considers other important aspects such as safety and sustainability. This system is a sustainable mechanism which is reusable in many operations, even for different kinds of operations. DCACLM reduces the use of temporary and auxiliary equipment, so the environmental impact is lower than using current systems.

Due to the importance of this mechanism, a new research line has been started in which the DCACLM will be manufactured and tested in order to determine the real behavior of the device. Laboratory tests will be compared with numerical simulation and the structural response of the mechanism in different situations will be verified. A 1:15 scale prototype will be manufactured and tested and the results obtained will be presented in a future research paper.

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