

ERECTION ENGINEERING OF PLATED STRUCTURES WITH COMPLEX GEOMETRY

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Keywords: Plated Structures, Erection engineering, Complex Geometry.

Abstract. *This paper is a knowledge share of the structural engineering analyses carried out for the safe erection of an architecturally innovative footbridge. The footbridge was composed of many different modules, each weighing 20 to 30 tons. These modules were all large welded plated structures made of a deck of about 10m by 8m and a single column each. The column's angle was different for each module and could be up to 45 degrees in any arbitrary direction. These modules were fabricated entirely on the shop and their transportation to the construction site included maritime and road transportation. Upon arrival on site, they had to be lifted and rotated by two cranes in tandem for their final installation. Initially, the design of the custom transport saddles is discussed. The geometric constraints made it impossible, during rigging, to properly align the lifting lugs to prevent the tilt of the module, thus there was a real risk of the module tipping over. The extensive and careful studies executed for the erection of each module is presented in detail and the possible solutions are discussed. Finally, the design of the lifting lugs is debated in detail, with a comparison of different types exposing their benefits and weaknesses.*

1 INTRODUCTION

The objective of this paper is to share the design experience of an architecturally innovative footbridge. This footbridge, situated in London, United Kingdom, was composed of 7 clusters that were linked by bridges. The constructed final bridge is shown in Figure 1.



Figure 1: Footbridge in London, UK. Source: [1]

A typical cluster composed of 3 modules is shown in Figure 2.

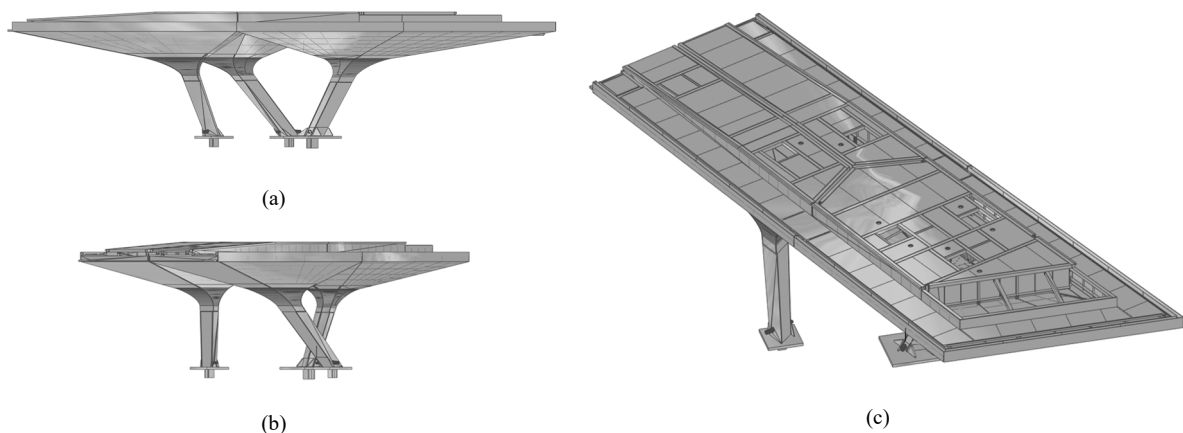


Figure 2: Typical cluster composed of 3 modules. (a) Front view. (b) Side view. (c) 3D view.

Each cluster was subdivided in modules for fabrication and for transportation. The number of modules that composed each cluster varied between 7 to 3 modules. Figure 3 displays the appearance a typical module.

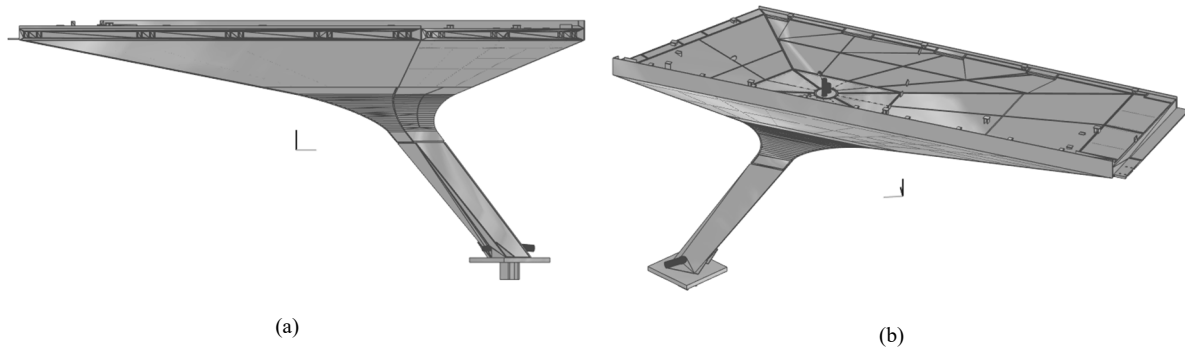


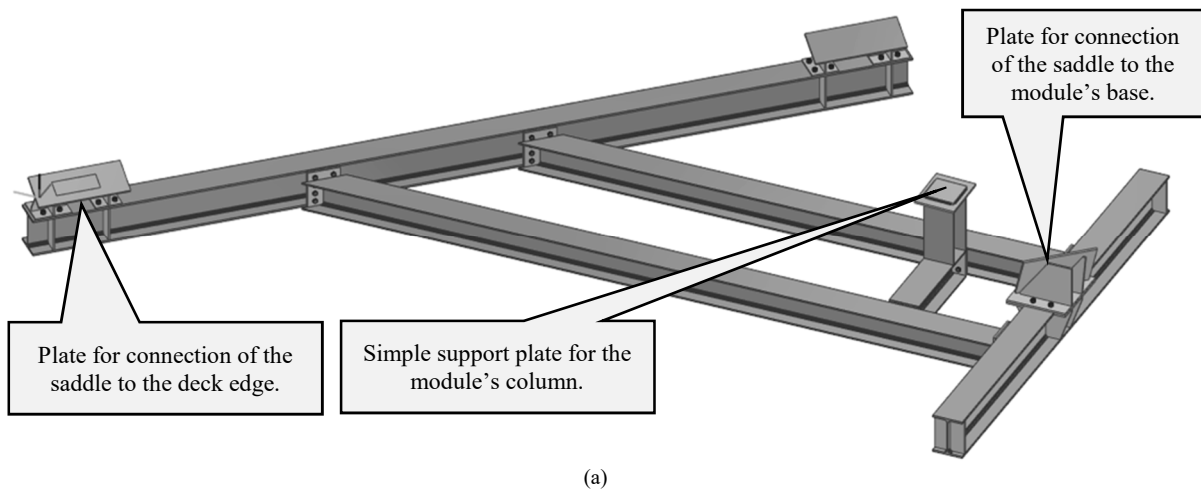
Figure 3: A typical module. (a) Front view. (b) 3D view.

Each of these modules was unique in geometry but they all shared the same basic characteristics:

- They were all fabricated using welded structural steel plates. Some plates (the ones directly linking the deck to the column) were curved.
- Their weight varied between 20 to 30 metric tons.
- They all had a deck that was *mostly* flat, but that had inclined planes converging at the point of origin of the column. This can be seen in detail in Figure 3 (b).
- Close to the centre of the deck a single column sprouted. The angle of the column relative to the deck was always different among the modules and was never perpendicular.
- The surface of the deck was about 10m by 8m. The height of the module (distance between the deck and the column base) was about 7m.

The modules were prefabricated in the vicinity of Venice, Italy. Their transportation from the shop to the construction site was multimodal and included both road and maritime transportation. For transportation, the modules were rotated as to have one of the edges of the deck parallel to the ground.

A unique saddle was designed and fabricated for each one of the modules. They were designed as to ensure the stability of the rotated module during the transportation. The bundle composed of the saddle and its module had to sustain acceleration loads due to the maritime transportation, lateral wind loading and its self-weight. Moreover, the bundle had also to be capable of being lifted horizontally as one piece for loading and unloading operation on its various means of transportation.



2 GENERAL DESIGN METHOD

Finite element method was used for the erection engineering design. Non-linearities such as material plastic deformation and contact elements were used. The element type was a mixture of 3D solid tetrahedral and quadrilateral elements considering mid-side nodes, together with 2D plate elements also considering mid-side nodes. The partial factors for design was done in accordance with the Eurocodes [2], as were the load combinations and the design acceptance criteria. The software used for the finite element analysis was Ansys 2019 R1 [3].

3 SADDLE DESIGN

The design of the saddles as shown in Figure 4 was done for the following design situations:

- STORAGE: When the bundle was resting above temporary stools.
- ROAD TRANSPORT: When the bundle was being transported above the deck of a self-propelled modular transporter SPTM.
- SEA TRANSPORT: When the bundle was being transported on the deck of a ship.

- LIFT: When the bundle was being lifted horizontally as, for example, when being handle in the harbour. Each design situation had different load patterns and had different support conditions.

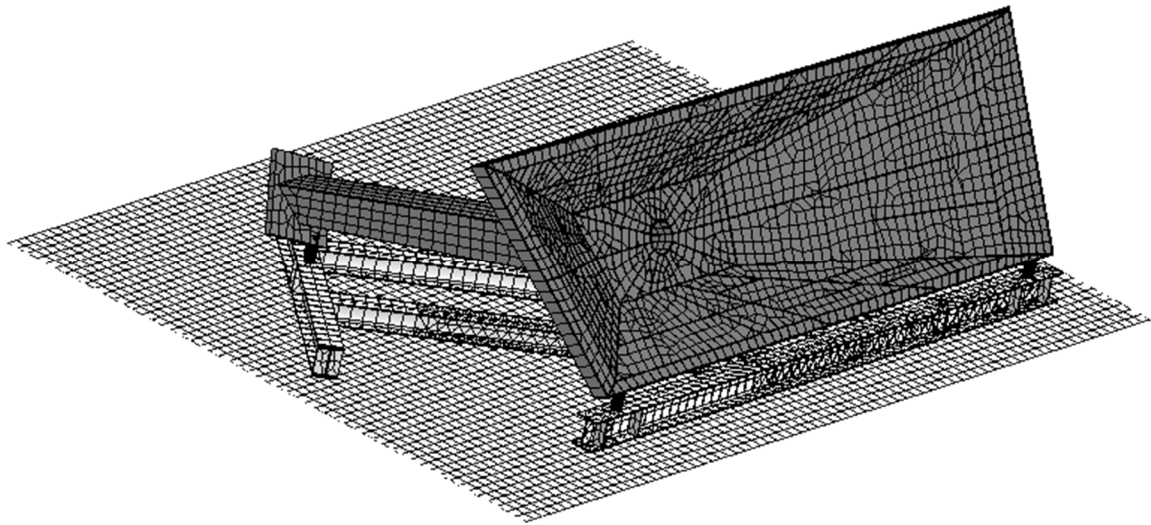


Figure 4: Typical saddle for transportation. (a) General design of the saddle. (b) Module rotated laying above the saddle.

Figure 4 illustrates the design of the saddle and the way the rotated module rested above it.

3.1 STORAGE: Bundle resting above temporary stools

The support condition of the bundle when resting above temporary stools, shown in Figure 5, was to have the support points modelled as simply supported. The design loads, considered and factored in accordance with the Eurocodes, included the dead loads and lateral wind loads relative to the harbour location with the highest wind speed (the fundamental wind velocity was taken as 30 m/s). Four different load cases were calculated to account for 4 different wind directions: +X, -X, +Y and -Y.

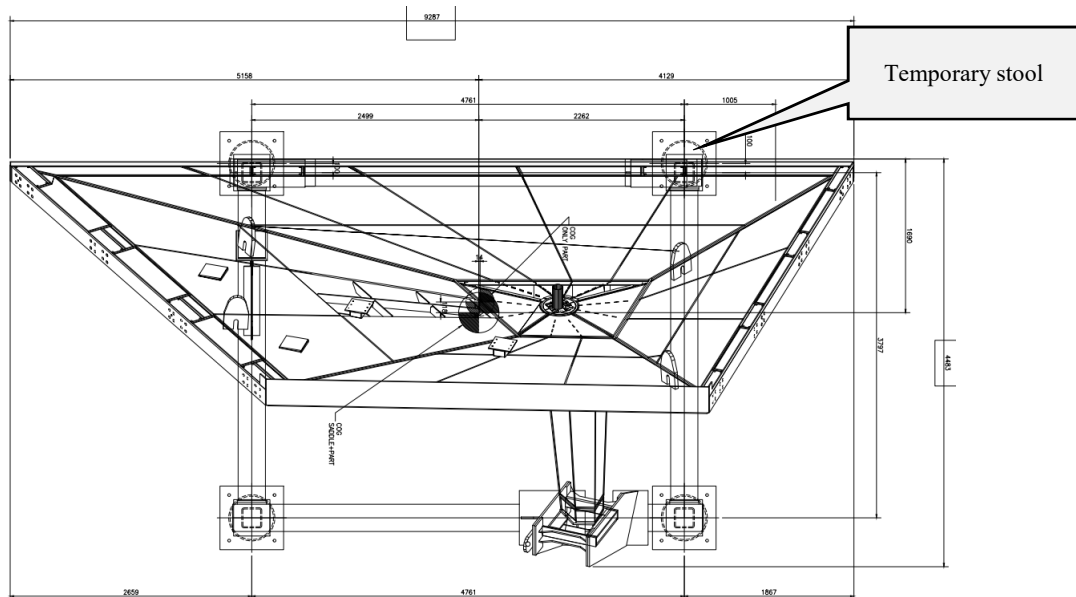


Figure 5: Top view of a bundle composed of the module and its saddle resting above temporary stools.

Figure 9 (a) exhibits the von-mises stress distribution found on the saddle and Figure 9 (b) shows the von-mises stress distribution found on the module for the -Y direction of the lateral loading, which is the direction that yielded the highest stress.

3.2 ROAD TRANSPORT: Bundle on SPMT

The support condition of the bundle when being transported above an SPMT, shown in Figure 6, was to model the surface of the SPMT as a rigid, fixed block. The lower surfaces of the saddle beams were set to be in frictional contact with this fixed block. The design loads, considered and factored in accordance with the Eurocodes, included the dead loads. It was considered that the road transport operation would be carried out in low wind, thus the wind load case was not included in the analysis.

During the road transportation, the deck of a SPMT may tilt to any side up to an angle of 8 degrees [4]. In order to simulate the possibility of tilting in the design analysis, the global orientation of the gravity acceleration was changes accordingly. 4 different directions for the tilting of the SPMT deck were considered: +X, -X, +Y, -Y.

An important point for the design of the road transportation using an SPMT is to ensure that the centre of the gravity of the object being transported is within the “triangle of stability” that is created by the lines interconnecting the centre of each hydraulic group that has been configured for the SPMT. This aspect was of profound importance for the design and stability checks for the road transportation of the saddle and module bundles, as, due to the height of the modules, their centre of gravity was also very high. One must always ensure that, regardless of the tilt that may occur on the deck of the SPMT, the centre of gravity will always fall inside the “triangle of stability”. Moreover, the changes in the location of the projection of the centre of gravity in relation to the “triangle of stability” also change the reaction on each hydraulic group. The designer must ensure that the hydraulic groups can sustain these loads for all situations. In-depth information for the design and stability checks for the usage of SPMTs may be found in [4].

Figure 10 (a) exhibits the von-mises stress distribution found on the saddle and Figure 10 (b) shows the von-mises stress distribution found on the module for the -Y direction of the lateral loading, which is the direction that yielded the highest stress. As one may see, the stress distribution on the saddle is considerably different than the stress distribution found for the STORAGE case.

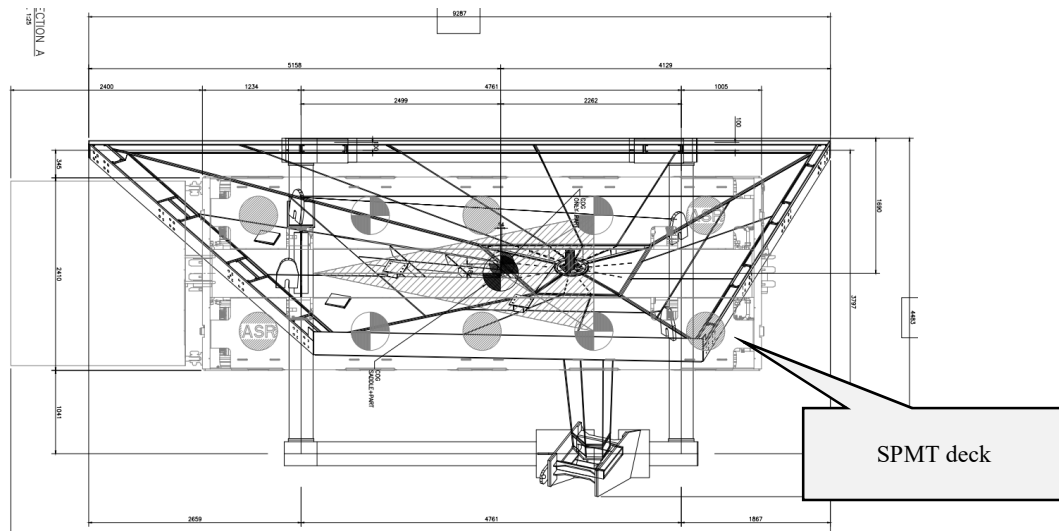


Figure 6: Top view of a bundle composed of the module and its saddle resting above the deck of a SPMT.

3.3 SEA TRANSPORT: Bundle on the deck of a ship

The support condition of the bundle when being inside the deck of a ship was to add to the lower surfaces of the saddle beams a frictional compression-only support. Additionally, it was considered that the lifting lugs of the modules, and the base of the modules, would be used to attach the sea fastening devices. This is illustrated in Figure 7.

The design loads, considered and factored in accordance with the Eurocodes, included the dead loads. It was considered that the bundle would be transported inside the cargo deck, protected from wind action, thus the wind load case was not included in the analysis.

Considerable acceleration must be considered for the design of the fastening scheme for a maritime transport. Values for the downward and sideways accelerations to be considered during maritime transportation are given in the International Maritime Organization’s guidelines [5]. The table here below is a reproduction of the information from those guidelines:

Table 1: Accelerations to be considered during maritime transportation.

Mode of transport	Forwards	Backwards	Sideways
ROAD	1.0g	0.5g	0.5g
RAILWAY			
Wagons subject to shunting*	4.0g	4.0g	0.5g (a)
Combined transport**	1.0g	1.0g	0.5g (a)
SEA			
Baltic Sea	0.3g (b)	0.3g (b)	0.5g
North Sea	0.3g (c)	0.3g (c)	0.7g
Unrestricted	0.4g (d)	0.4g (d)	0.8g

The value of $\pm 0.8g$ for the acceleration was considered for both the downwards and lateral acceleration. This was due to the fact that the value $\pm 0.8g$ downwards was most penalizing for the design of the saddle and module bundle, a part of the maritime transportation would go through the Atlantic and the placement (orientation) of the bundle on the ship was unknown at the time of analysis.

As the sea fastening scheme considered that the lifting points of the module would be used for their attachment, an output of the design was a table with the force reactions on each of these support points. This information was then passed on to the responsible party for the sea transportation for their definition on the sea fastening elements. A scheme of this is shown in Figure 7.

Figure 11 (a) exhibits the von-mises stress distribution found on the saddle the +Y direction of the lateral loading and Figure 11 (b) shows the von-mises stress distribution found on the module for the -X direction of the lateral loading. These are the directions of the acceleration that yielded the largest stresses in these items. As one may see, the stress distribution on the saddle is considerably different than the stress distribution found for the other cases, specially as there is loading on the lifting lugs.

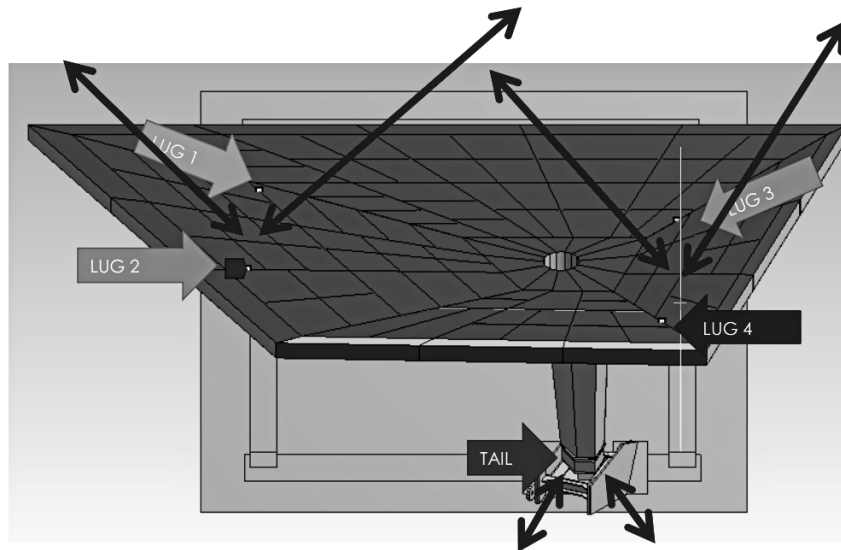


Figure 7: Sea fastening reaction scheme.

3.4 LIFT: Bundle being lifted horizontally

The design for lifting of the bundle composed of the saddle together with its module included the definition of the sling arrangement, which is shown in Figure 8. The sling arrangement made use of a spreader beam to ensure the verticality of the lower slings. The sling was connected, on one side, to the base of the column. On the other side, two slings were connected to two of the four lifting lugs of the modules.

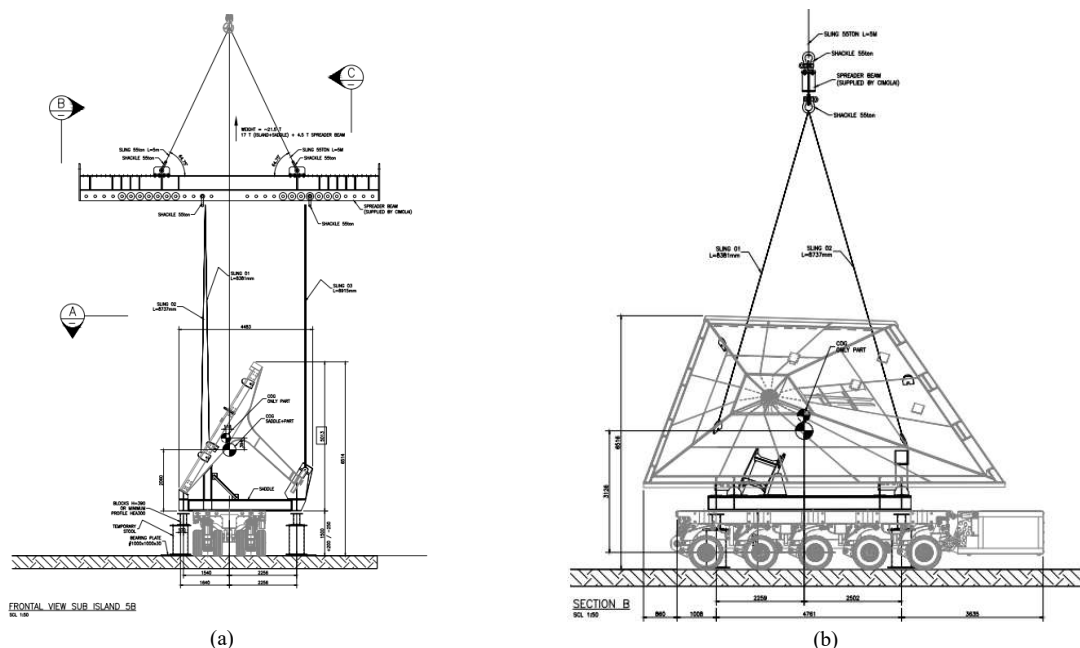


Figure 8: Sling arrangement for lifting of the bundle composed of the saddle and the module.

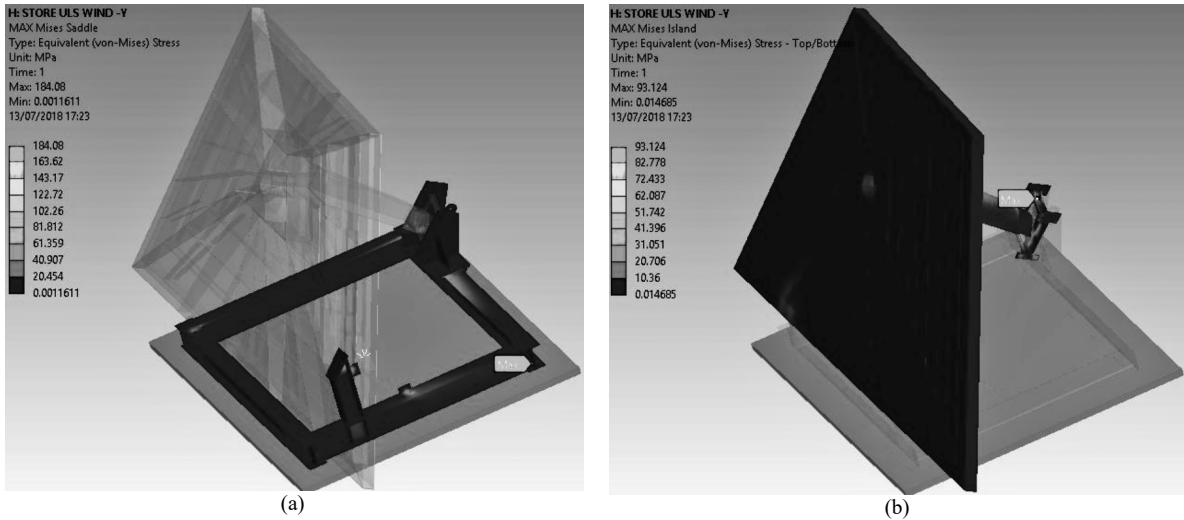


Figure 9: Von-mises stress distribution for the **STORAGE** design situation for the direction -Y. (a) Von-mises stresses found on the saddle members and (b) Von-mises stresses found on the module.

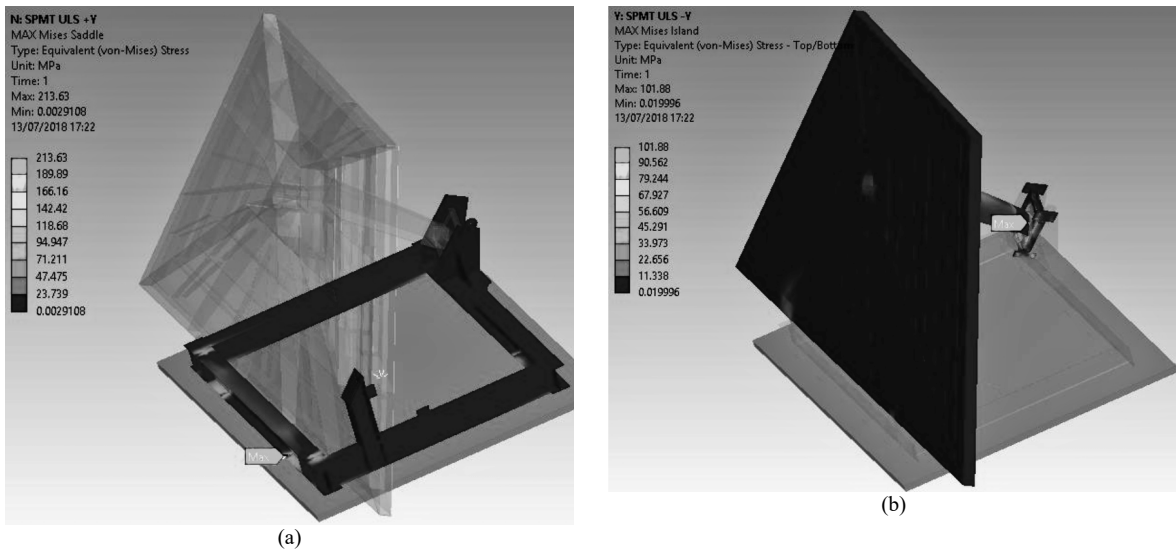


Figure 10: Von-mises stress distribution for the **ROAD TRANSPORT** design situation for the direction +Y. (a) Von-mises stresses found on the saddle members and (b) Von-mises stresses found on the module.

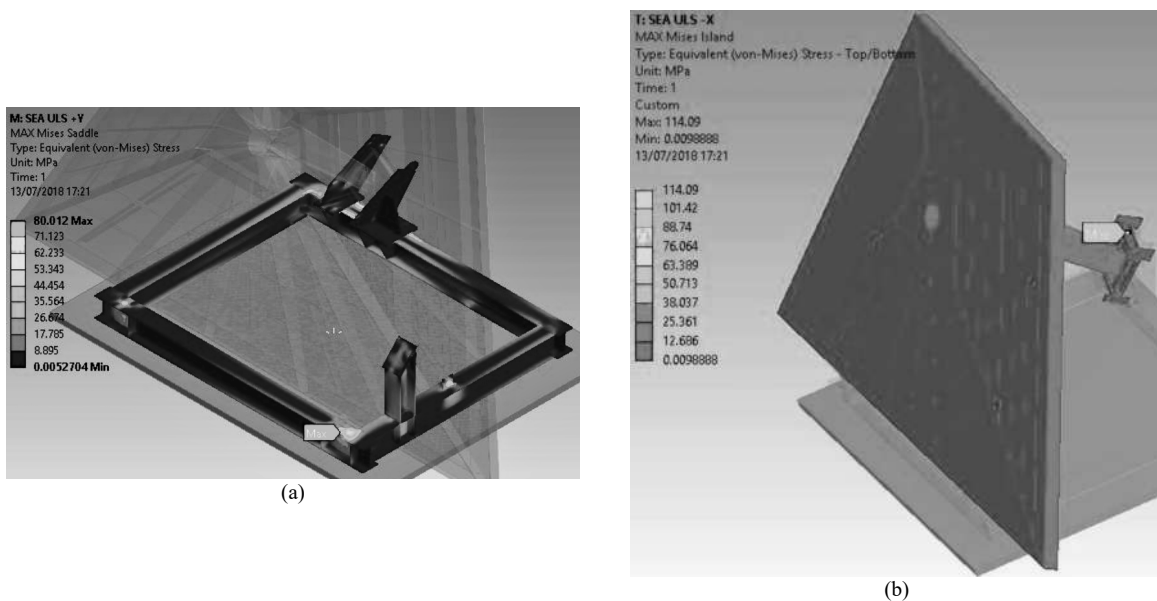


Figure 11: Von-mises stress distribution for the **SEA TRANSPORT** design situation. (a) Von-mises stresses found on the saddle members for the direction +Y and (b) Von-mises stresses found on the module for the direction -X.

As the position of the lifting lugs of the modules was defined by constraints due to the module's rotation for installation (see section 3), the length of each lower sling was carefully defined in order to minimize any tilting of the bundle while on the air. The fine adjustment of the sling arrangements was done using chains of shackles, a practice allowed by their manufacturer [6]. This is exhibited in Figure 12.

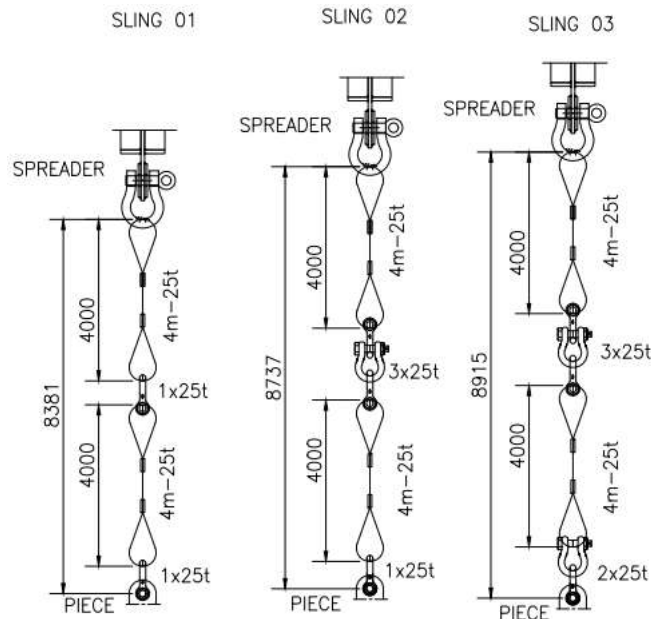


Figure 12: Length adjustment of the lower slings for the horizontal lifting of the bundles.

The verifications of the slings and of the design of the lifting lugs was carried out in accordance with the BS EN ISO 19901-6:2009 [7]. This standard, although targeted for the offshore industry, contains valuable guidelines in its chapter 18 for the design of any heavy lift operation.

3 MODULE ROTATION FOR INSTALLATION

After the arrival of the modules on site, these had to be rotated on the air so that their deck and the baseplate of the columns would be parallel to the ground. The rotation operation was carried out using two cranes, a main crane and a tailing crane. The rotation operation presented a number of challenges that were due to the geometric characteristic of the modules.

The first challenge was directly related to the positioning of the top lifting lugs. As illustrated in Figure 3 (b), the deck of the modules was not flat. It had inclined planes converging at the column. In some modules, this inward inclination of the deck planes made the positioning of the lifting lugs very difficult, specially the lifting lugs that would be in higher elevation at the beginning of rotation operation. Additionally, it was a request from the client that clashes caused by the placement of the lifting lugs with secondary elements of the structure should be avoided.

Another aspect that greatly complicated the design of the rotation operation was that angle of the columns relative to the horizontal plane. Their skewed aspect rendered impossible the proper alignment of the tailing lug located at the base of the column with the top lifting lugs. The line connecting the two top lifting lugs that are active at the beginning and earlier phases of the rotation operation (Figure 13: Line 1) was impossible to be perpendicular to the line passing through the tailing lug and centre of gravity of the lifted module (Figure 13: Line 2). This is shown in Figure 13.

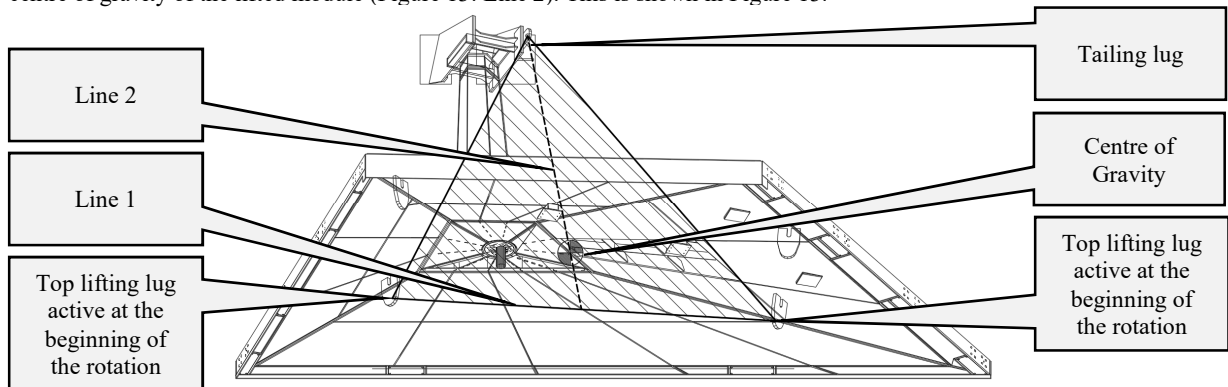


Figure 13: Top-down view of the beginning of the rotation operation. The lines 1 and 2 are not perpendicular.

The phases of the rotation operation are shown in Figure 14. The misalignment of lines 1 and 2 of Figure 13 causes a tilting of the module around its axis as the rotation operation is carried out.

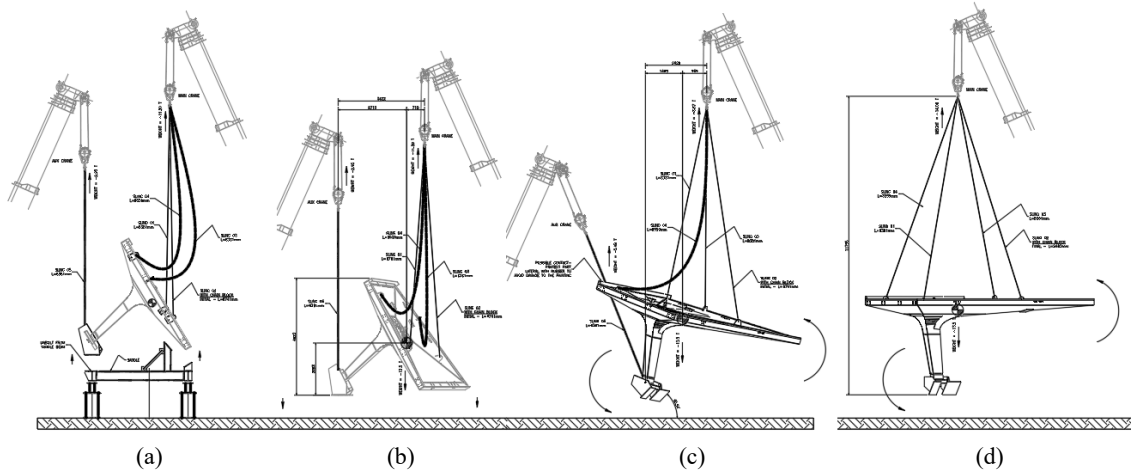


Figure 14: Phases of the rotation operation. (a) Initial phase: release of the module from the saddle. (b) Early rotation phase with only 2 top slings activated. (c) Later rotation phase with 3 top slings activated. (d) End of rotation with 4 top slings activated.

The tilting of the module around its own axis during the rotation operation is, in this case, very dangerous. The tilting of the module changes the projection onto the horizontal plane of not only the module’s centre of gravity, but also the projection of the activated lifting lugs as well. As it can be seen in Figure 14 (a), the centre of gravity of the module is *above* the triangle of stability created by the projection onto the ground plane of the 2 top activated lugs and the tailing lug.

If the tilting of the module is high enough (which was the case for most of the modules), as the rotation operation progressed, the projection of the centre of gravity would fall out of the triangle of stability. Since the centre of gravity of the module is above the plan passing through the three pick points, when the projection of the centre of gravity goes outside the triangle of stability, the module would quickly spin (tip over) around its axis to bring the centre of gravity to be under the pick points. This quick rotation would entangle the slings, add considerable dynamic effects into the lifting system and certainly cause the collapse of the operation.

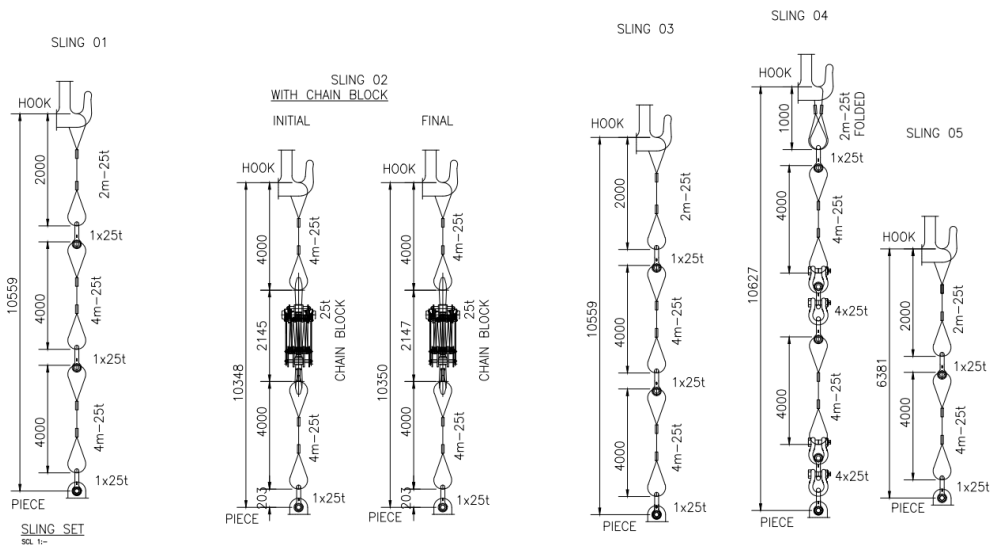


Figure 15: Detail of the sling arrangement length. Sling 01 to 04 are the top slings and sling 05 is the tailing sling. Note the come-along on sling 02 to allow the change in sling length and thus the deck alignment after the end of the rotation operation.

In this project the designers prevented the tipping over of the module by a careful study on the sling arrangement and sling length. This is shown in Figure 15. The basic design idea was to carefully control the length of the third top sling. The third sling started the rotation operation as a loose cable. As the rotation advanced, and thus also the tilting, the third cable got more and more taut. When the third cable got fully taut, the third sling was activated. The activation of the third sling locked the tilting of the module from that point on, effectively ensuring the safety of the rotation operation. This mechanism is shown in the photographs of the actual operation displayed in Figure 16.



Figure 16: Phases of the rotation operation. (a) Beginning of the rotation operation. (b) Activation of the third top sling preventing additional tilting of the module. (c) Last phase of the rotation operation.

Another point of attention was that, due to the inclined orientation of the columns and the size of the module's deck, it was impossible to prevent the touching of the trailing sling with the module's deck as shown in Figure 16 (b). This is acceptable as long as the contact of the sling to the object is not against a live edge (risk of sling rupture) and as long as the rotation operation is carried out in a way in which no lateral loads are imposed onto the boom of the trailing crane. This can be done by, for instance, releasing the rotation of the trailing crane around its own axis.

After the rotation operation was finished, as shown in Figure 16 (c), the length of the slings were adjusted with the provided come-alongs (hand operated winch) to align the deck and the base plate of the module to the horizontal plane for its installation. See Figure 15 for the sling arrangement detail.

4 DESIGN OF THE TOP LIFTING LUGS

The geometric restrictions on the positioning of the lifting lugs, as well as requirements for the rotation and tilting of the module for installation, added an increased level of complexity to the design of the lifting lugs.

The platted elements composing the modules' decks was made of radial stiffeners. Transversal stiffeners connected these radial stiffeners. On the edges of these elements were welded the plates that composed the deck's inclined plane. The general topology is shown in Figure 17.

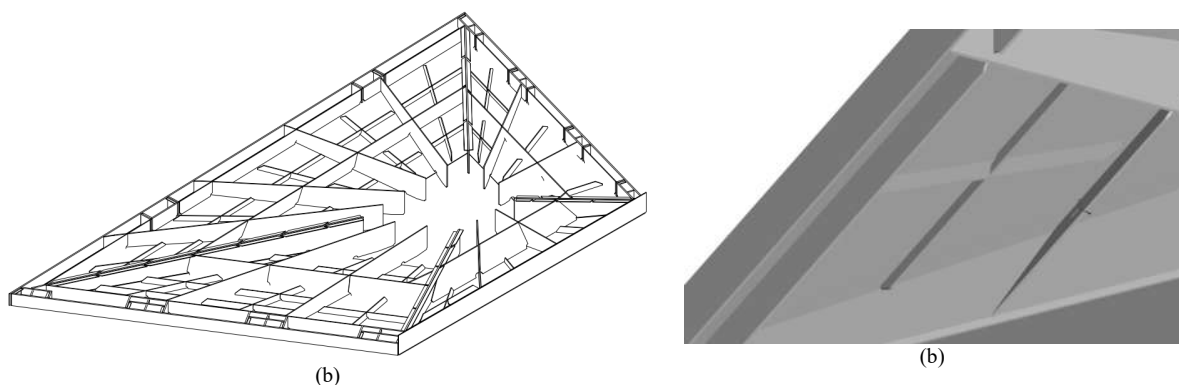


Figure 17: General typology of the inner construction of the top deck of the modules. (a) Inner radial and transversal stiffeners. (b) Deck view from the bottom, with the bottom plates hidden, showing the top plate and its stiffeners.

Several iterations were carried out for the general philosophy of the design and placement of the lifting lugs.

Lifting lugs with pads welded onto the stiffened top plates gave a good flexibility for the positioning and orientation of the lifting lugs, but, due to the closed construction of the deck, it was impossible to weld the top plate's stiffeners to the main radial or transverse stiffeners of the deck. This restriction caused problems with the buckling of the top plate, of its stiffeners and they concentrated the loads at the edges of the top plate elements, which had a weak weld to the main stiffeners.

The typology for the design of the top lifting lugs that yielded the best results in terms of flexibility of positioning and on strength requirements was to weld the lifting lugs onto the main radial or transversal stiffeners. It is shown in Figure 18. The only revision required on the deck's plates was a small cut at the edges of the top plates to accommodate the thickness of the lifting lug's plate. Another advantage is that the weld of the lifting lug was then loaded mainly in shear.

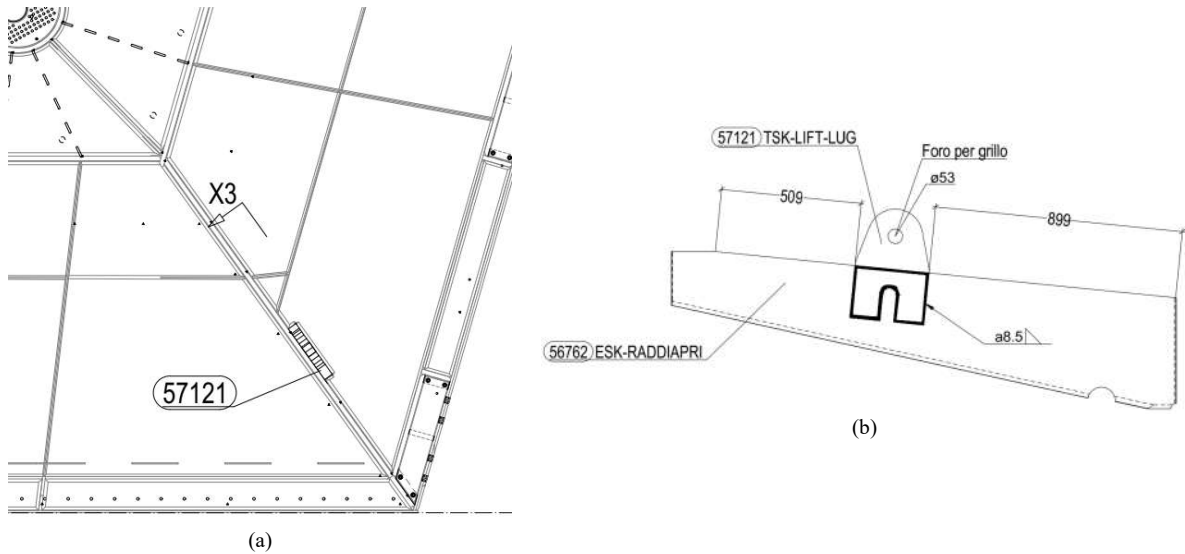


Figure 18: Typology of lifting lug. (a) Top view of showing the lifting lug plate and the cut at the edge of the top plate. (b) Side view of the lifting lug welded to the main radial stiffener.

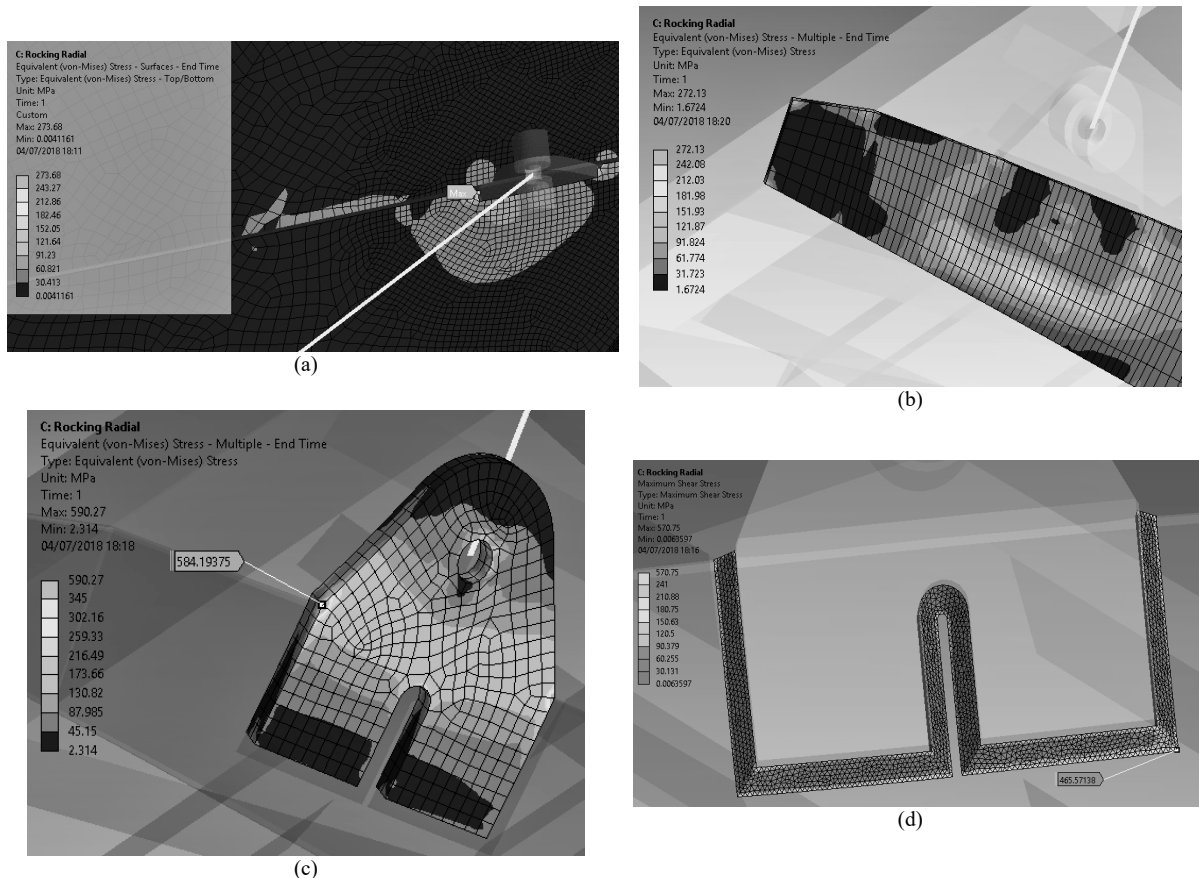


Figure 19: Von-mises stresses of lifting lug and the elements in its vicinity. (a) Stress distribution on the deck top plate. (b) Stress distribution on the radial stiffener. (c) Stress distribution on the plate of the lifting lug. (d) Stress distribution on the weld.

The loading situations of the lifting lugs were also uncommonly special:

- The general typology of having the lifting lugs welded onto the main radial or transverse stiffeners limited the possible orientations of the lifting lugs.
- The lifting lugs were used in various different loading angles and conditions, as the same lifting lugs were used to manipulate the bundles composed of the saddle and the horizontal module.

- The rotation operation changed by itself the direction of the applied load onto the lifting lugs, a behaviour that was amplified by the tilting of the module during the rotation operation as described in section 3.

Therefore, it was unavoidable to have lateral loads acting on the lifting lugs. To account for these lateral loads, the analysis of the lifting lugs was carried out for various load conditions, including the modules lifted with their saddles and various steps of the rotation operation (0 degree, 30 degrees, 45 degrees, 60 degrees, 80 degrees and 90 degrees, as well as the angles on which the activation of the third sling occurred). Additionally, load factors for the design of pick points in accordance with [7] were considered, with special note to the rocking requirements due to the usage of 4 slings without a spreader bar at the end of the rotation operation.

Figure 19 exhibits a typical result for the design of a lifting lug welded to a radial stiffener. Figure 19 (a) and Figure 19 (b) show that the module's plates are not overstressed. Figure 19 (b) shows that the lifting lug plate suffers considerable bending action due to the side action. A 40mm plate was required for the plate of the lifting lug to safely take this bending effect.

5 CONCLUSION

This paper is a knowledge share of the engineering analyses that have been conducted for a plated structure with a very complex geometry. The geometric arrangement posed challenges for the transportation of the modules from the shop to the site and for the rigging of the modules for installation. Saddles constructed specially for each and every module have been designed using finite element analysis for various load situations, ranging from storage to sea transportation. The rigging for installation presented stability issues that have been overcome with the careful design and positioning of the lifting lugs and the in-depth studies on the rotation/tilting of the modules so that the tilting of the module is stopped (and thus ensuring the stability of the operation) by tauting a third set of slings.

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