Joint Simulation With Shear Key And Wedge Effect For Lightweight Precast Slabs

Simulación De Junta Con Llave De Cortante Y Efecto De Cuña Para Losas Prefabricadas Ligeras

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ABSTRACT

Roofs and mezzanines built with lightweight prefabricated elements have two major drawbacks: the longitudinal joints between elements and the permeability of said joints. If continuity is to be achieved in the slab, a joint is required to guarantee the transmission of stress to the adjacent elements, and its design to ensure the watertightness of the slab and the slab in general. The present study was focused on a joint with a shear key and wedge effect, which had already been used in the Residential Building System (SER) with good structural results, but not from the point of view of waterproofing. Based on this, it was decided to analyze the behavior of two types of joints, one completely filled with resistant mortar and the other applying an adhesive, waterproofing and elastic material in the lower part of the joint, filling the rest of the cavity with mortar. In the study, the Finite Element Analysis was carried out in several scenarios, with slabs of 3.61 m in length. With the results, it was possible to verify that the two types of joints have a favorable structural behavior before the application of the loads, perceiving that the slabs are deformed as a whole and with small displacements. This confirms that type 2 joint can be used for roofs and wet areas of mezzanines, guaranteeing both resistance and structural rigidity, as well as impermeability.

Keywords: *analysis, deformations, displacements, joint*

RESUMEN

Las cubiertas y entrepisos construidos con elementos prefabricados ligeros presentan dos grandes inconvenientes, las juntas longitudinales entre elementos y la permeabilidad de dichas juntas. Si se pretende lograr la continuidad en la losa, se precisa de una junta que garantice la transmisión de los esfuerzos a los elementos contiguos, y que su diseño asegure la estanqueidad de las mismas y de la losa en general. El presente estudio estuvo enfocado en una junta con llave de cortante y efecto de cuña, la cual ya había sido utilizada en el Sistema de Edificaciones Residenciales (SER) con buenos resultados estructurales, pero no desde el punto de vista de la impermeabilización. A partir de esto se decidió analizar el comportamiento de dos tipos de juntas, una completamente llena de mortero resistente y otra aplicando un material adhesivo, impermeabilizante y elástico, en la parte baja de la junta, rellenando el resto de la cavidad con mortero. En el estudio se realizó el Análisis por Elementos Finitos en varios escenarios, con losas de 3.61 m de longitud. Con los resultados se pudo constatar que los dos tipos de juntas tienen un comportamiento estructural favorable ante la aplicación de las cargas, percibiéndose que las losas se deforman como un conjunto y con desplazamientos pequeños. Con ello se corrobora que la junta tipo 2 puede ser utilizada para cubiertas y zonas húmedas de entrepisos garantizando, tanto resistencia y rigidez estructural, como impermeabilidad.

Palabras claves: análisis, deformaciones, desplazamientos, junta

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1. INTRODUCTION

The construction of mezzanines and roofs using lightweight precast reinforced mortar elements has proven to be advantageous compared to conventional heavy technologies from several points of view: cost, speed of construction, weight, volume of material, aggregate, steel and cement expenditure, resistance to earthquakes and hurricanes, energy consumption, and others [1, 2]. It is also known that all prefabricated mezzanines and roof require special attention to the design of the joints between slabs [3]. Since a technology for prefabrication is being redesigned, it's necessary to take in account not only slabs and joints, but, additionally, static molds, slip form machine, auxiliary devices, matrixes and other technological parts of the system need to be considered. That's why is being integrally applied a parametric engineering design method [4, 5], which requires to make quick analysis of slabs shape, to probe design concepts in early stages of the design process. The side shape of slabs corresponds with a "type 1" mortar joint with shear key and wedge effect (Figure 1) which has been already structurally tested in several building, but it is not waterproof. Therefore, type 1 joint is not useful in the construction of roofs or wet parts of mezzanines, if it is not combined with other waterproofing methods [6, 7]. For this reason, it has been proposed to execute a "type 2" joint (Figure 2), which combines two materials in the same type 1 joint space: an initial, very elastic adhesive mixture at the bottom of the joint, which forms an impermeable interface with the slabs and a resistant mortar at the upper part [8]. The impermeability of the assemble is based on the fact that the adhesive elastic mix and the reinforced mortar slabs are waterproof [2, 9], so, guaranteeing the water tightness of the joints, the roofs and the mezzanines will not require an additional waterproofing system to fulfill this function. During design process of the technology, it is then necessary to decide if it's possible to keep the same molds, executing type 2 joints and making impermeable the roof or the mezzanine with no losing stiffness and resistance. For that is enough to theoretically analyze stresses and deformations of the floor with type 2 joint comparing result with type 1 one. The shear key functioning is based on the grip that occurs between the slab and the mortar of the joint. The mortar-slab adherence is not enough to transmit significant loads, so frequently slabs are designed with a specific geometry which transmits forces to the neighboring slabs by direct thrust, achieving better load distribution and reducing deformations of the mezzanine under loads. In case of imminent slippage, if the interface mortar-slab geometry forms an inclined plane, high normal forces are produced, so lateral thrust between sabs consequently grows and adhesive forces in the interface are amplified. This wedge effect puts the slabs in a such stress state to better resist applied loads. The type 1 joint has a shear key with wedge effect, so is expected that type 2 joint will work preserving the lateral geometry of the slabs and keeping the functionality of the shear key and the wedge effect of the type 1 joint.

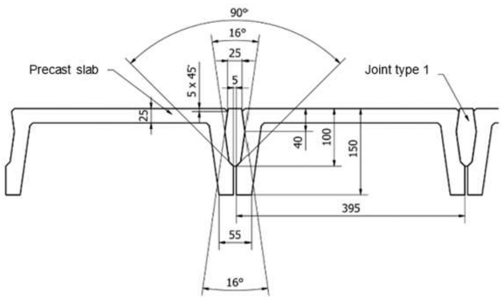

***Figure 1:** Details of gasket type 1 joint*

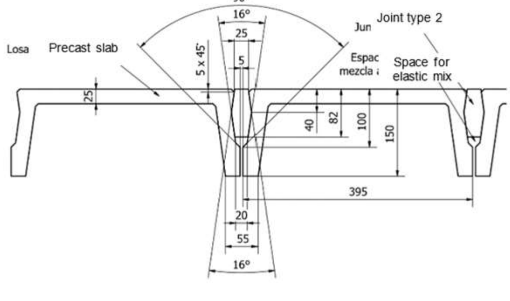

***Figure 2**: Details of the type 2 joint*

Finite Elements Analysis (FEA) is a useful tool for joints analysis and evaluation in prefabricated buildings. In [10] analyzed joints between wall panels using FEA structured models with brick type elements, obtaining information about failure process of the joints. Luo et-al [11] analyze Beam-Column joints using structured FEA experimental constitutive model, using structured 8 nodes bricks elements to deeply study reinforced concrete with the aim of predict seismic behavior of the joint using equivalent constitutive relation. In [12] are studied composite slabs using structured brick elements too for seismic behavior analysis. In general, for precise researches are used structured brick elements, but, because of the high performance of new work stations it is possible to use tetrahedral elements saving time without losing precision. Design is a time-consuming activity, that's why Computer Aided Design (CAD) systems have an internal Finite Elements Analysis (FEA) complement, helpful in fast modeling and simulation of the most frequent mechanical systems. In this particular case authors use, to analyze the joints, the internal FEA complement of Autodesk Inventor Professional 2020, and the CAD system that is used to design the system of molds and other technological manufacture equipment.

The aim of this paper is then to make a FEA evaluation of the structural behavior of type 2 joint to take preliminary decision in early stage of mechanical technological equipment design.

2. MATERIALS AND METHODS

2.1 Simulation by finite elements

Through the AEF module of the CAD system, analyzes are carried out that consider deformable solids, assuming here a homogeneous and isotropic material with the characteristics shown in Table 1, which is accepted as an approximation of the operation of the system, because the slabs are always going to be made of resistant mortar with a highly distributed reinforcement, for example, ferrocement [7].

Table 1: *Characteristics of the material used in the AEF model*

Portland Cement Mortar			
Mass Density	2.24 g/cm^3	Young's Modulus	14 GPa
Yield Strength	20 MPa	Poisson's Ratio	0.2 ul
Ultimate Tensile Strength	2 MPa	Shear Modulus	5.83333 GPa

Two scenarios are studied, scenario 1 model is represented in Figure 3, it focuses on simulating the work of three slabs together with their joint. Seven solids elements were generated: three slabs, two joints, both 3.61 m long, and two elements that represent load-bearing walls (visible under the slab extremes). The slabs were supported 60 mm at each end on the walls, mobility was restricted, so that the slab-wall link was made through contact joints that allow the separation of the elements and their sliding without friction, but not penetration. Thus, it is sought that the behavior of the slab-wall joint is very close to the so-called "simple support". The same type of contact was established between slabs and joints, at the same time that the external sides of the lateral slabs were limited in their horizontal displacement by adding contact joints between the lateral external surfaces of the lateral slabs and the upper protrusions of the extremes of the walls. This is the case in the most of actual construction, where the mezzanine of a rectangular room, for example, is confined on all four sides. With the intention of analyze the stress transmission to the lateral slabs, distributed vertical load of 5000 Pa (design load) was applied to the described multiple solid system on the upper surface of the central slab. A downward gravitational field was activated (Figure 3).

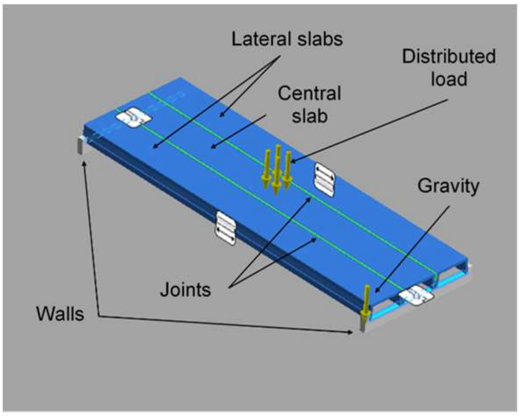

Figure 3: *Model for AEF, scenario 1. Slabs simply supported at their ends, joints and slabs with the possibility of sliding and separating. Weight force and distributed load of 5000 Pa*

In the meshing of the model (for both joint types), the maximum sizes of the elements in the central slab and the joints were limited to 5 mm, and in the lateral slabs to 100 mm, which was decided after a convergence analysis in three steps with 1% difference in Von-Mises equivalent maximum stress (Figure 4). It was payed more attention to the central slab and to the joints, that´s why the smaller elements on their meshing. FEA of CAD systems generally work with tetrahedral elements, because it´s facilities for automatic complex shapes meshing. Even when other elements and structuration could be less time consuming, authors consider that is not necessary to emigrate to another software in the middle of the design process. In the model is assumed that the elastic adhesive mix (not defined for now) doesn´t participate in the load transmission, due to its very low stiffness compared to the joint and slab mortars.

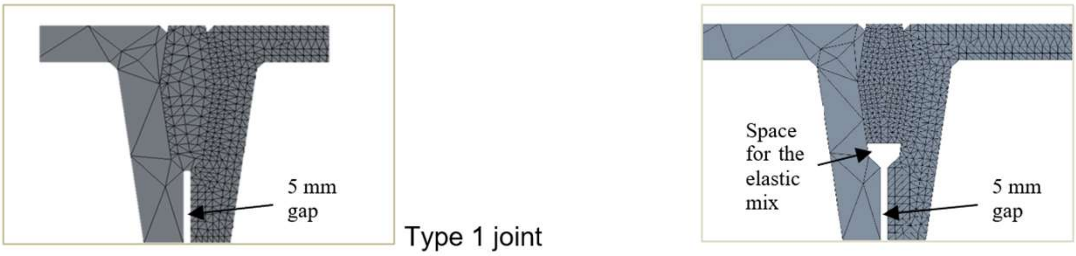

***Figure 4:** The mesh characteristics of the model are the same in both joint types.*

To make useful comparisons, a scenario 2 was analyzed, which consists on deactivating the contacts between the joints and the slabs to obtain the deformations and stresses that occur just in the central slab, the only loaded element (Figure 5), so that it is possible to quantify the contribution of each type of joint to the distribution of the load between several slabs.

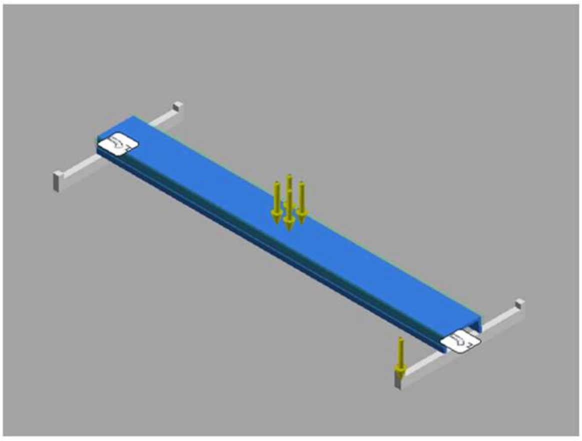

***Figure 5:** Model for AEF, scenario 2. Central slab simply supported at its ends, with no link with the side slabs. Weight force and distributed load of 5000 Pa*

3. RESULTS AND DISCUSSION

3.1 AEF results for the model

Figure 6 shows notable reference points numbered from 1 to 9. In Figure 7 and Figure 8 it can be seen that, using either of the two joints, the vertical deformations occur in all the slabs and not only in the one that is loaded, which is a consequence of the fact that an important part of the load is transmitted through the joints. Type 1 provides a slightly lower deformation at the center of the central slab (point 5) than type 2; although in both cases they are small, 4.69 mm and 5.15 mm respectively (11% increase), which is also visible in Figure 7 and Figure 8. The displacements relative to a point on the side slab (point 9 in Figure 6) are shown in Figure 13. Note that, for point 8 (lower end of the flange in the middle section of the central slab) the relative displacements are 0.46 and 0.75 mm for the cases of type 1 and type 2 joint respectively, two values considered small compared to the dimensions and general deformations that occur in the system, despite being 60% greater in the type 2 joint.

It is assumed that the material of the slabs has a high degree of distribution in the reinforcement, be it steel or polymer reinforced with glass fibers, carbon or other material. Due to this, it can be considered that the reinforced mortar has a homogeneous and isotropic behavior, which is why the Von-Mises stresses, as long as they do not exceed the order of 5 MPa, are useful to give an idea of the operation of the set of slabs. Contrasting Figure 9 with Figure 10 , it is observed that, the stresses are transmitted from one slab to the other with practically the same effectiveness through both types of joint, a little better with the type 1 joint, which makes the lower part of the central slab (point 7 of Figure 6) a stress of 4.85 MPa versus 5.52 MPa in the case of the type 2 joint. Figure 11 shows the 1st principal stress in an independent slab loaded with 5000 Pa on the upper surface and at Figure 12 also graphs the contact pressures, the values being quite small. The pressures are not worrisome from the point of view of resistance, as corroborated in Figure 13 . The 1st and 3rd main stresses in notable points of the central slab and the joints in scenario 1 for AEF are shown in the Figure 14.

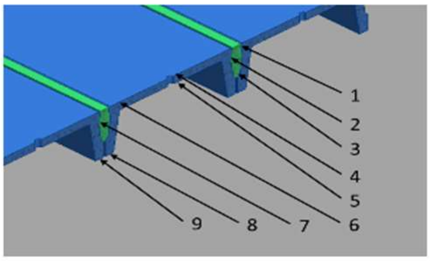

Figure 6. *Remarkable points in the middle traversal section of the slabs and joints. Points 1, 2, 3 and 7 are located in the joint; points 4, 5, 6 and 8 are located in the central slab; and point 9 is located in the lateral slab.*

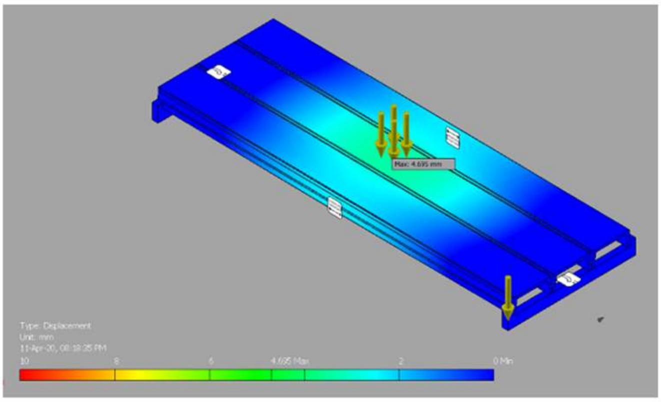

Figure 7: *Vertical deformations in scenario 1, joint type 1. The maximum value (4.69 mm) occurs at point 8 (referenced in Figure 6), located at the end of the flange, in the middle section of the central slab Note that the deformation is shared with the side slabs.*

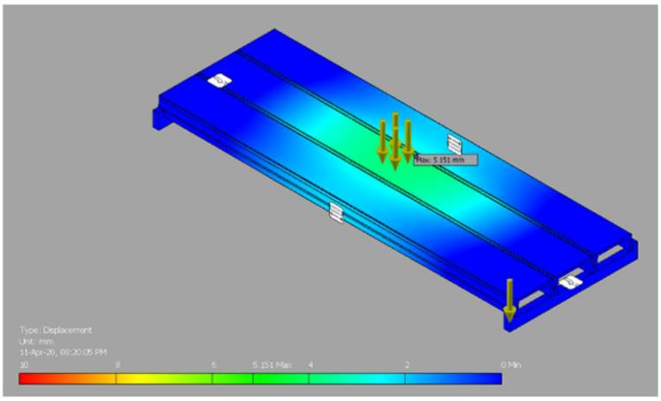

Figure 8: *Vertical deformations in scenario 1, joint type 2. The maximum value (4.69 mm) occurs at point 8 (referenced in Figure 6), located at the end of the flange, in the middle section of the central slab. Note that the deformation is shared with the lateral slabs.*

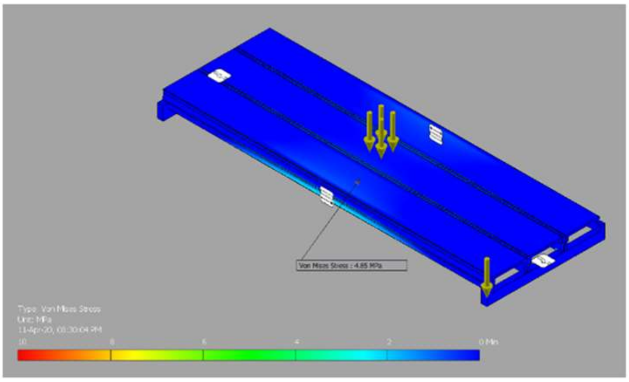

Figure 9: *Von-Mises stresses in scenario 1, in point 8 (referenced in Figure 6), for the case of type 1 joint (0 to 5 MPa on the color scale).*

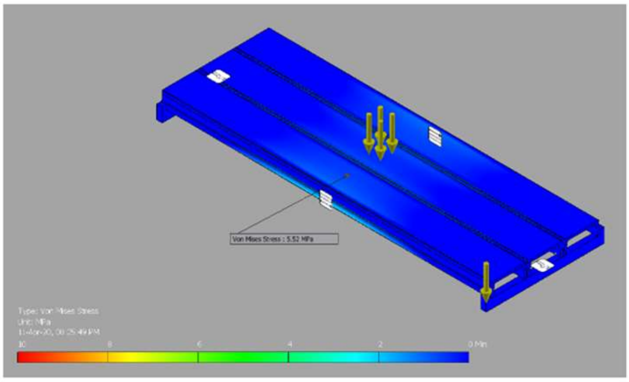

Figure 10: *Von-Mises stresses in scenario 1, point 8 (referenced in Figure 6), for the case of type 2 joint (0 to 5 MPa on the color scale).*

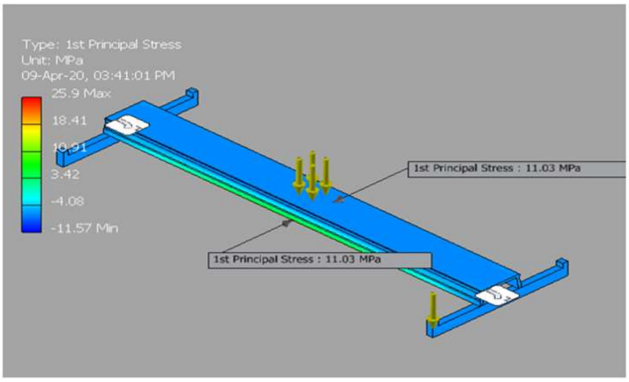

Figure 11: *1st principal stress (normal tensile stress, predominant at the lowest part of the middle transversal section) in an independent slab loaded with 5000 Pa on the upper surface (scenario 2). The maximum value, at point 8 (referenced in Figure 6), is 11.03 Mpa.*

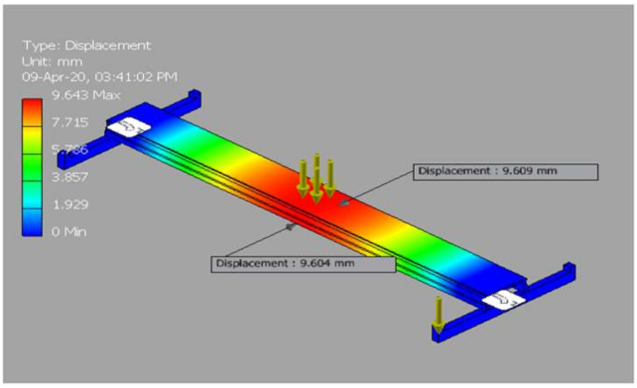

Figure 12: *Vertical displacement in an independent slab loaded with 5000 Pa on the upper surface (scenario 2). The maximum value, at point 8 (referenced in Figure 6), is 9.6 mm.*

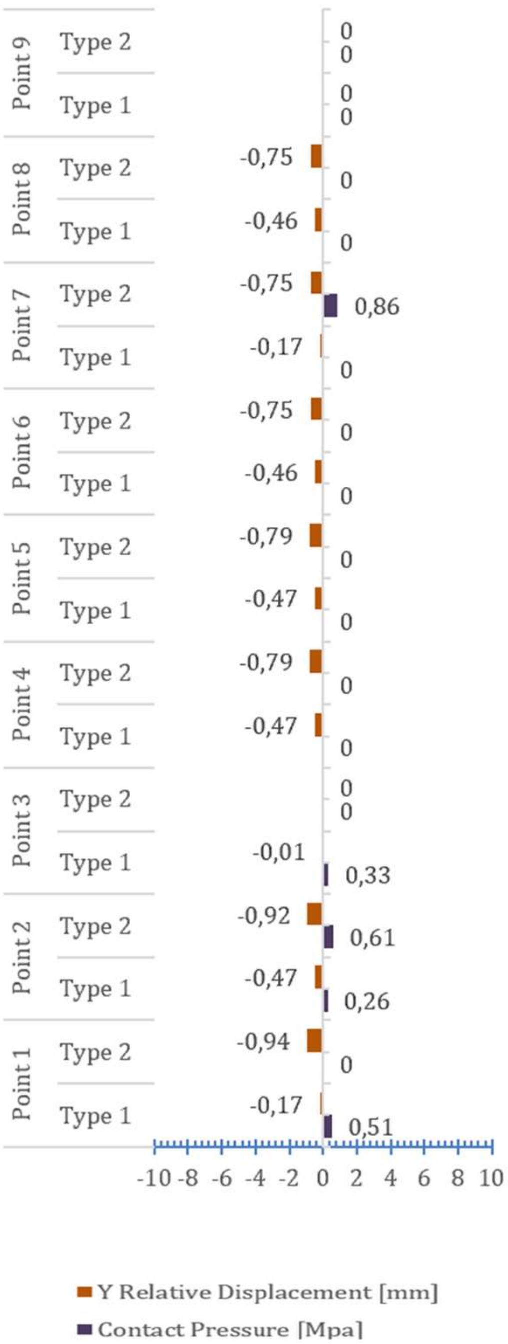

Figure 13: Contact pressures and relative vertical displacements at notable points of the central slab and joints, scenario 1, for AEF

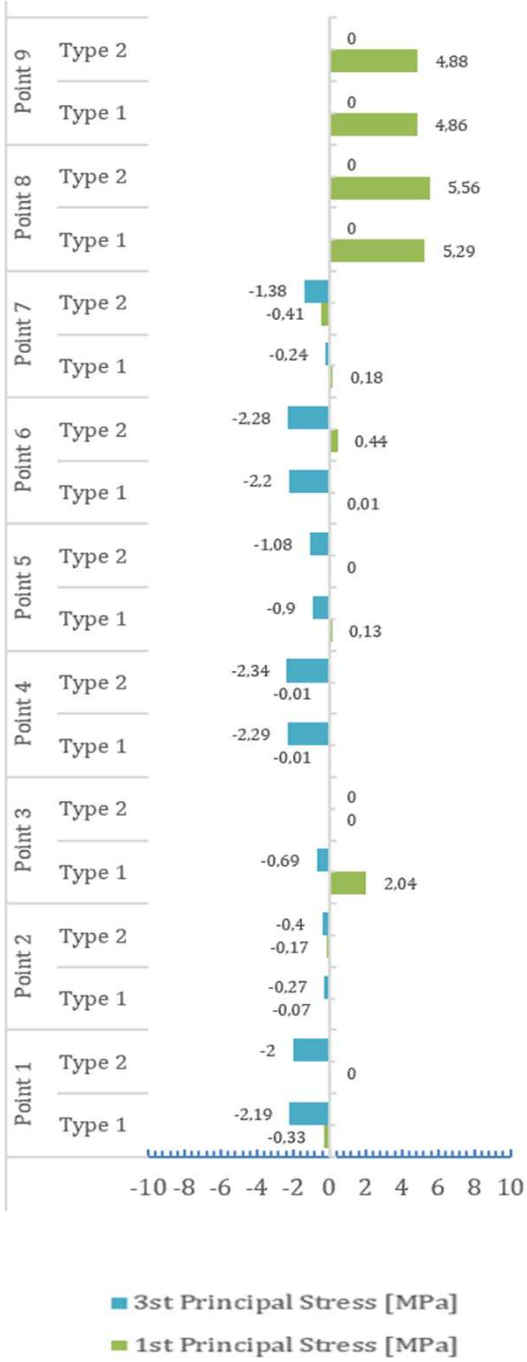

Figure 14: 1st and 3rd main stresses at notable points of the central slab and joints, scenario 1, for AEF

4. CONCLUSIONS

From the simulations and analyzes carried out, it can be affirmed that the two types of joints can be used safely for mezzanines and roofs. The analysis of deformations and stresses show that these do not exceed the admissible values that were taken for the study. The stresses are transmitted through the joints with a shear key, transposing part of the loads from the central slab to the neighboring slabs. The wedge effect participates in the load transmission to the neighboring slabs, providing values lower than the permissible ones. However, a very important aspect is that the type 2 joint, in addition, can guarantee the impermeability in the roofs and wet areas of mezzanines by applying, in the free space, a waterproofing and elastic material, which is capable of withstanding the stresses and environmental conditions. Without losing, during the useful life of the building, the features that ensure the tightness of the joints. Finally, it's possible to sustain that it's not necessary to design different molds, manipulation tools, and other technological equipment to prefabricate slabs corresponding to type 1 and type 2 joints.

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