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STUDY OF THE LOADING ARRANGEMENT FOR THE STIFFNESS TESTS OF THE COLUMN HEAD ASSEMBLY AND ITS SPRINGS UTILIZED AT THE NIARCHOS CULTURAL CENTER AT ATHENS - GREECE.

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Abstract. *This paper presents the loading arrangements that were conceived and constructed in order to tests in prototype scale the performance of the suspension devices (Column Head Assembly specimens) that are part of the total suspension system of the roof deck that will be constructed at the top of the Stavros Niarchos Foundation Cultural Center that is currently constructed at Athens, Greece. Each suspension device utilizes 4 springs with a tensile capacity of two hundred tons and a corresponding extension of 300mm and two dampers with a maximum damping force of the order of 10tons. These springs and dampers form together with a stiff steel reaction frame and a sliding billet the column head assembly (suspension device) with overall dimension approximately 4.4m x 4.4m in plan and 2.5m height. The billet can slide vertically within the core of the column head assembly approximately 250mm and withstand a vertical force of the order of 300tons. In order to test the performance of these column head assemblies at the laboratory prior to their being used in-situ a special loading arrangement was manufactured at the laboratory of Strength of Materials and Structures of Aristotle University. The basic loading functions of the suspension system of the roof deck that is to be constructed at the Stavros Niarchos Foundation Cultural Center is briefly described as well as how this was simulated at the laboratory of Strength of Materials and Structures of Aristotle University in order to measure the performance of prototype suspension device specimens prior to being installed in-situ. A special loading rig was designed and finally constructed to be utilized in the prototype testing of the performance of the springs. A series of linear and non-linear numerical simulations were employed towards securing the safe performance of this loading rig during the testing of the said springs.*

1 INTRODUCTION

This paper presents a summary of experimental procedures that were utilized to measure at the laboratory environment the basic components of a suspension system that is designed to be utilized in the suspended roof that will be built at the top of the building complex of the "Stavros Niarchos Foundation Cultural Center" that is currently constructed in Athens, that will be designated in the following as NCC. The drawing image of the NCC complex is depicted in figure 1a where it can be seen that the aerodynamically shaped hollow concrete roof deck is supported by a series of slender steel columns [1]. This hollow roof deck is formed by joining in-situ pieces of double relatively thin-skin cross-sections stiffened with vertical webs that are pre-constructed by fero-cement and specially formed steel reinforcement, as shown in figure 1b. The system that this roof is suspended from will not be visible as it will be built within the space left by the top and bottom thin skin faces of the hollow roof deck.

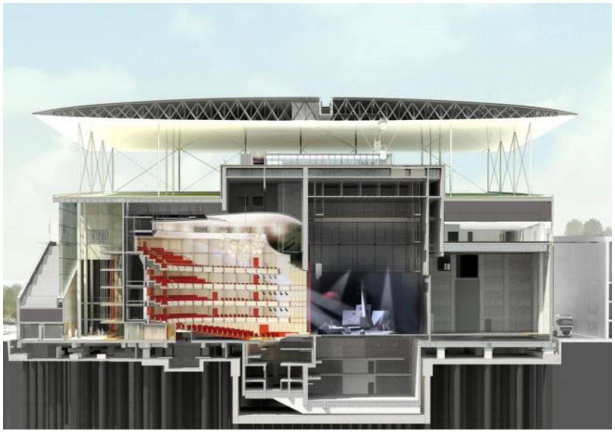


Figure 1a. Suspended roof of the Stavros Niarchos Foundation Cultural Center

Figure 1b. Parts of the suspended roof made of fero-cement and steel reinforcement

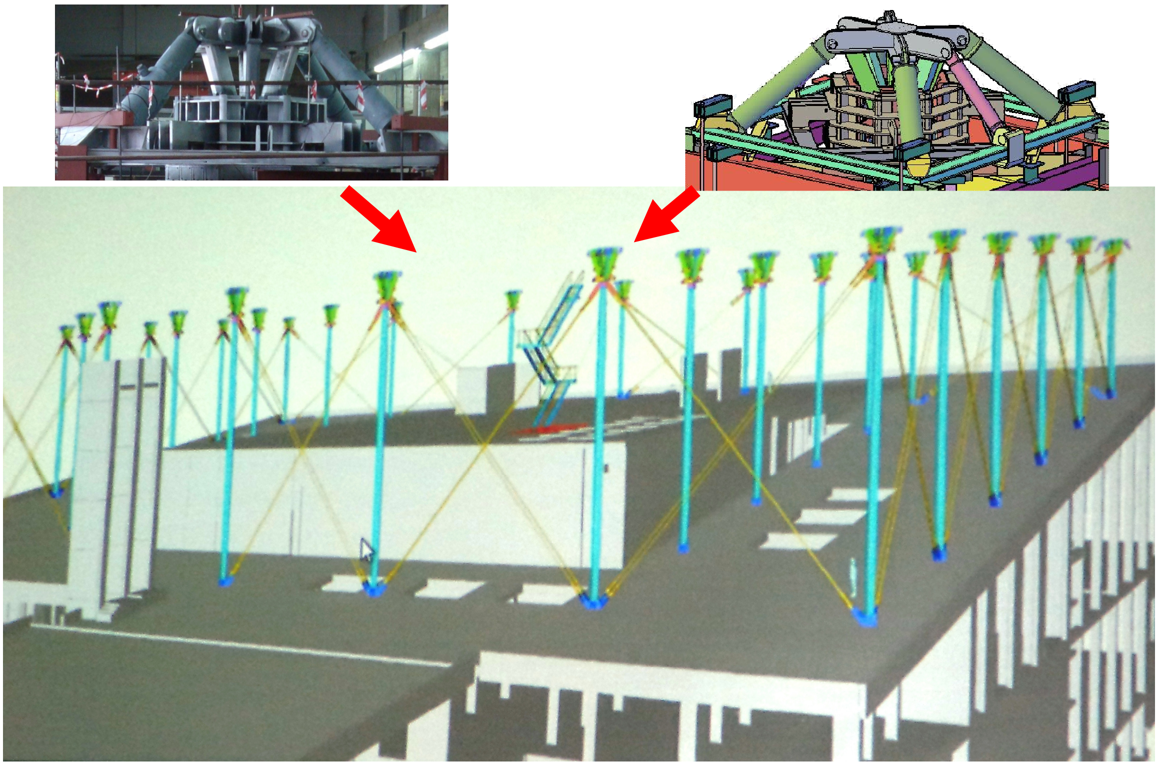


Figure 2. The supporting columns with the suspension devices shown schematically without the roof deck

The concept of this suspension system is shown schematically in figure 2. On top of every column a suspension device is constructed. These suspension devices are all the same for all columns that are named Column Head Assembly Type-4 (designated as CHA Type-4) except the four corner columns that are named Column Head Assembly Type-1 (designated as CHA Type-1). Each suspension device is formed by the following components:

Figure 3. The horizontal strong square steel frame with the hollow cylinder at the center

a) A horizontal strong square steel frame shown in figure 3 that is constructed with four corners where this frame is joined to the concrete deck and at the same time provides the bottom hinged support of the four springs that form the suspensions system. At the center of this strong frame a strong hollow cylinder is formed with a number of polygonal webs from the outside and four identical vertical cylindrical surfaces from the inside that are constructed with special sliding material.
b) A steel sliding core "billet" which is shown in figure 4 in its temporary supports. This sliding core (billet) of the suspension system is shown in figure 5 as it is lowered in a inside the hollow cylinder of the strong steel frame. This billet provided at its top hinged support for the springs of the suspension system.

Figure 4. The sliding core "billet" temporary supported outside of its host-steel frame

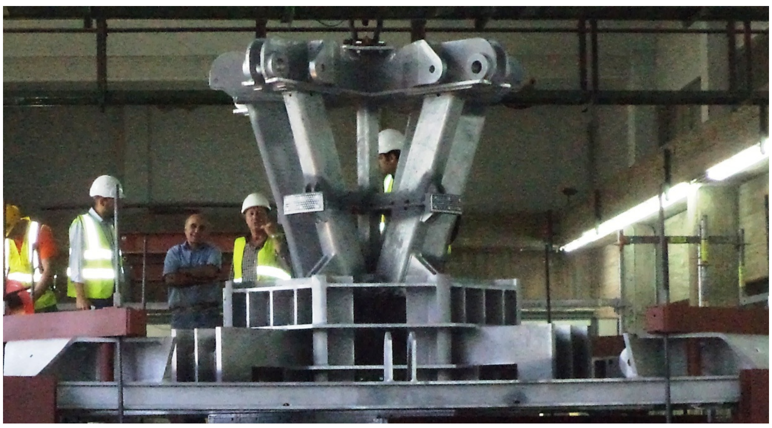


Figure 5. The sliding core "billet" being lowered in position within its host-steel frame

c) Four identical springs having the required stiffness properties that join at their bottom end the four corners of the strong steel frame with the four hinges of the billet at their top end. This is depicted in figure 6. When the four corners of the steel frame do not bear any load the billet is at its lowest possible position and the springs are in their contracted length. At this condition, the only load that is transferred at the bottom of the billet being supported at the top of the steel columns is the dead load of the components of this suspension system that is of the order of 50KN. When the four corners of the strong steel frame are forced downwards with extra vertical load the this results in an extension of the spring by such a length that is required to equilibrate this vertical load. There are two types of springs. The ones depicted in figures 6 and 7 that belong to the CHA Type-4 specimen and are longer than the springs for the CHA Type-1 specimen that is depicted in figure 8.

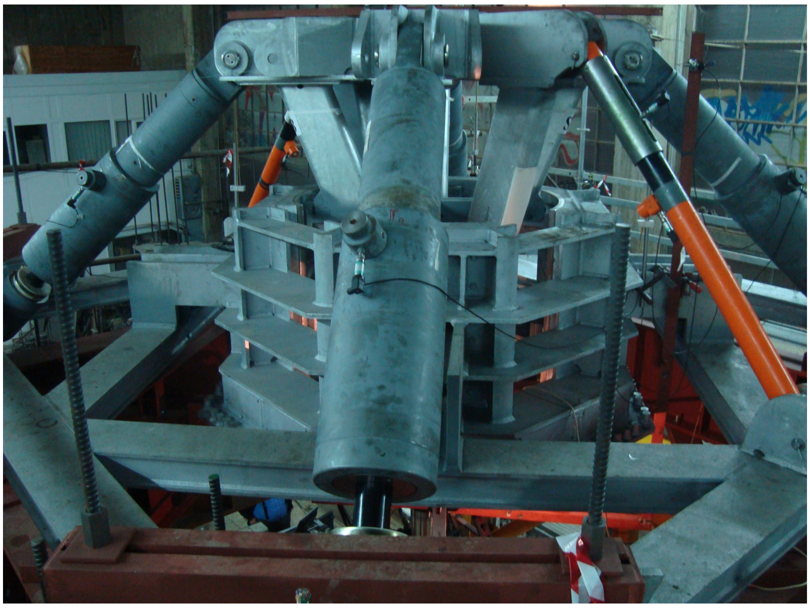


Figure 6. The sliding core "billet" in position within its host-steel frame and springs and dampers

d) Two dampers (new dampers type-4 with the orange colour), that also join the top of the billet with the strong steel frame as shown in figure 6. Similarly, there are two types of dampers; first, the ones that belong to the CHA Type-4 specimen (figures 6 and 7) that are longer than the ones that belong to the CHA Type-1 specimen (figures 8 and 9)

Figure 7. Springs and old dampers for CHA Type-4

Figure 8. Springs for CHA Type-1

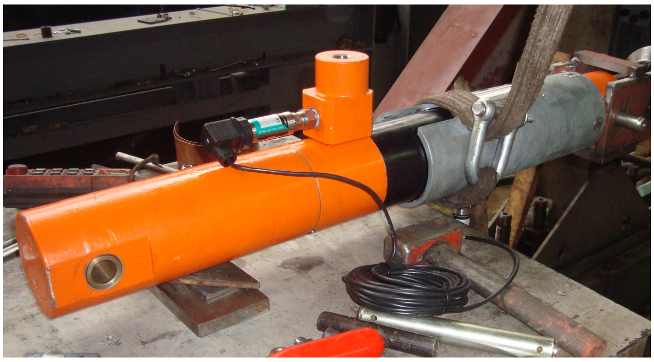


Figure 9. Springs for CHA Type-1

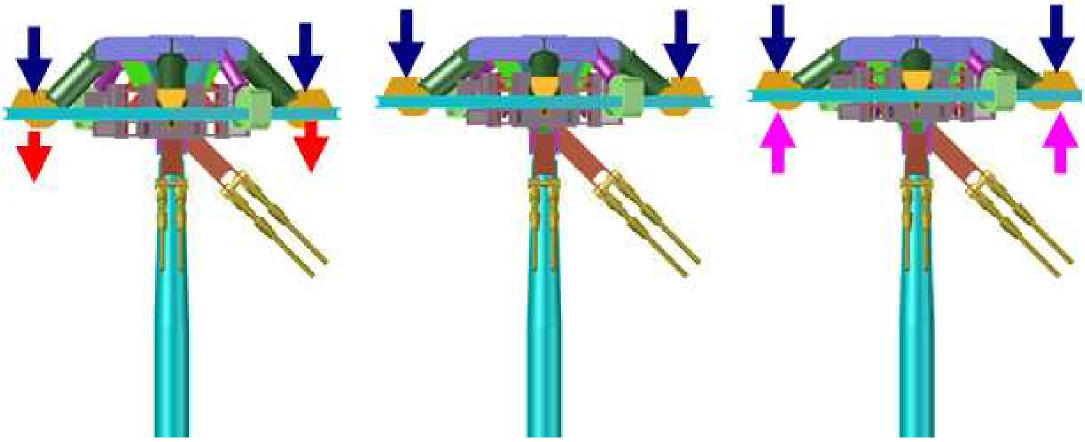


Figure 10. Loading function of the suspension device

2 BASIC LOADING FUNCTIONS OF THE SUSPENSION DEVICE AND EXPERIMENTAL SIMULATION

2.1 Basic loading function of the suspension device.

Figure 10 depicts the basic loading function of the suspension devise. The sketch in the middle of this figure depicts the suspension device carrying the dead weight of the roof deck (blue arrows). To perform this function, the following steps are necessary.

a) The springs are initially extended, without internal forces, at a certain pre-determined length that corresponds to a relative zero condition. This initial extension of the springs corresponds to a vertical upward displacement of their upper length relatively to their bottom end which means that at this initial zero condition the billet has also being moved upwards by sliding into the hollow cylinder at the appropriate location which represents for the billet the initial zero condition. At this initial zero condition the lower corners of the springs and the corresponding corners of the horizontal steel frame are secured being in contact with the corresponding host steel brackets embodied in the low thin-skin of the roof deck. At this stage the suspension devices are not carrying any of the roof deck load, as it is still supported by the temporary shoring.

b) Then, by applying the appropriate external pressure in the four springs simultaneously, the springs are developing internal tensile forces that step-by-step pick-up some portion of the dead weight of the roof deck.
c) This operation is performed in turn gradually for all the suspension devices until the sum of the tensile forces that are exercised by the four springs of each suspension device to the roof deck equilibrate its total dead load. At this point, the roof deck is suspended from the suspension system being freed from the temporary shoring which can thus be removed.
d) With the suspension system at this Dead-Load condition when extra vertical load is applied downwards on the roof (snow, wind, seismic etc.) then the springs will be further extended in length to equilibrate this extra vertical load (red arrows, figure 10 left). This is possible, by an additional upward vertical displacement of the ends of the springs being hinged to the billet, which in turn slides upwards within the central hollow cylinder. The system at this condition has the springs extended to their maximum allowable length developing at the same time the maximum internal tensile forces that through the sliding “billet” core are transferred as maximum compressive vertical reactions on top of the steel column supports.
e) With the suspension system at this Dead-Load condition when extra vertical load is applied upwards on the roof (wind, seismic etc.) then the springs will be shortened in length appropriately to equilibrate this extra vertical load (pink arrows, figure 10 right). This is possible, by a downward vertical displacement of the ends of the springs being hinged to the billet, which in turn slides downwards within the central hollow cylinder. The system at this condition has the springs contracted to their minimum allowable length developing at the same time the minimum internal tensile forces that through the sliding “billet” core are transferred as minimum compressive vertical reactions on top of the steel column supports.
f) The above steps d and e can also be seen in combination as being able to have each suspension devise being displaced from the condition where the springs have their minimum length and very little tensile force (zero load and zero vertical displacement condition for the billet being at its lowest level) to the condition where the springs have their maximum length and their maximum internal tensile force (maximum load and maximum vertical condition for the billet being at its highest level). This rational will be made use of during the experimental process.

2.2 Experimental simulation of the basic loading function of the suspension device.

In order to study the performance of prototype suspension device specimens at the laboratory the rational stated in section 2.1. (step f) above was utilized [2]. That is a prototype suspension device with all its parts being the prototype components was secured at the laboratory environment at a condition representing the minimum length of the springs condition section 2.1. (step e). At this geometry of the suspension device the corners of the horizontal steel frame were secured on the strong reaction steel frame of the laboratory of Strength of Materials and Structures as it is shown in figure 11. This was achieved by a system of pre-stressing steel rods. Moreover, with the suspension device fixed in this geometry the point where the sliding billet is supported on the prototype steel columns in-situ was secured here by supporting it to the rod of a hydraulic jack. This rod could be displaced upwards by a control system exercising in this way an upward force to the billet which by being equilibrated by the four springs would result to the springs being extended by the appropriate amount whereas at the same time the “billet” will also slide upwards by the corresponding amount of vertical displacement. This operation could be applied on a continuous manner till the suspension device reached the conditions with the four springs being extended at their maximum limit length which would correspond to the maximum upward vertical sliding displacement of the billet within the hollow steel cylinder. This condition corresponds to step d) above and obviously requires from the hydraulic jack to be able to apply a vertical force and a vertical displacement that corresponds to the maximum level of forces the suspension device would develop during step d). This was approximately of the order of V=3000KN and δ_v = 250mm. This is depicted in figures 11 and 12.

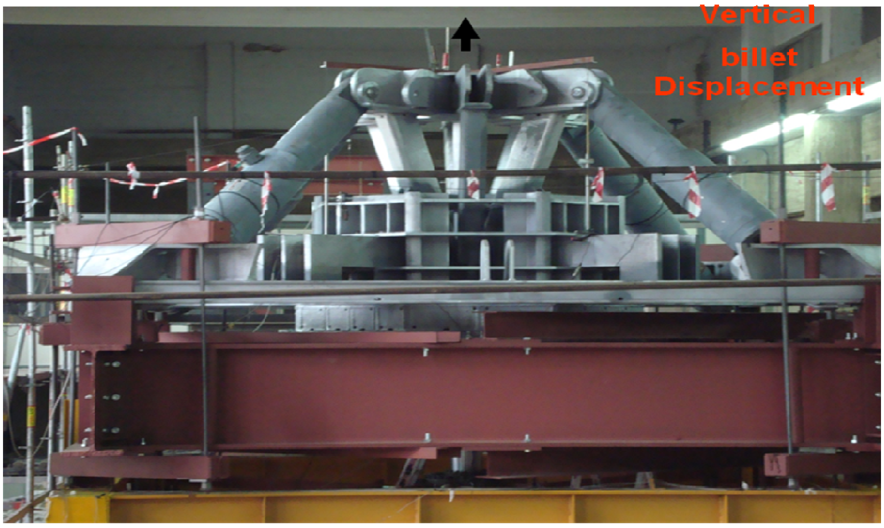


Figure 11. The suspension device CHA Type-4 being supported at the strong reaction frame

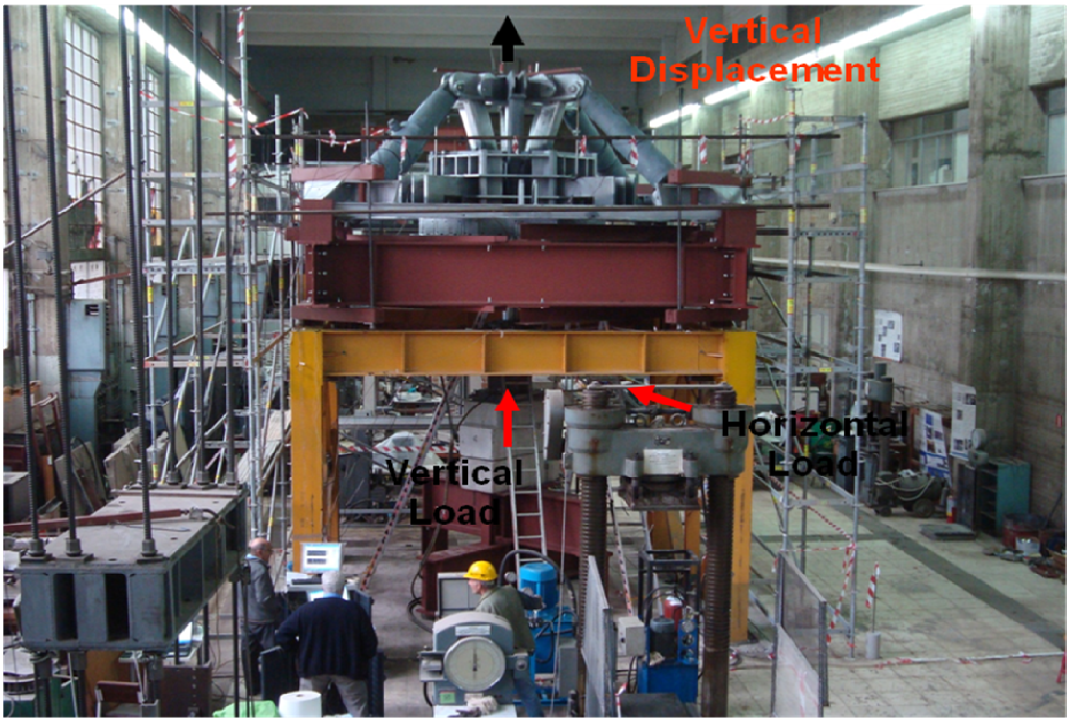


Figure 12. The suspension device CHA Type-4 being supported at the strong reaction frame (brown and yellow colour) together with the hydraulic jack installed in a way to apply the required vertical load at the center of the billet

With this laboratory loading arrangement (figures 11 and 12) the basic loading functions of the prototype suspension device in-situ (section 2.1) was simulated in laboratory conditions. Two suspension devices were tried; the first on that was designated as CHA Type-4 and the 2nd one that was designated as CHA Type-1 (see introduction). A considerable number of tests were performed for each suspension device varying the following parameters:

a1) The inclusion during testing in the device of the relevant two dampers. Thus the same tests were repeated with and without the two dampers.

b1) The simultaneous application at the low part of the billet a certain level of horizontal load, as shown in figure 12, in order to check the performance of the device when apart from the upward and downward displacement each device was subjected to a certain level of bending moment with a tendency to create a rotation φ1 of the billet relative to the surrounding hollow steel cylinder, as is shown in figure 13. This horizontal load was applied through an additional horizontal hydraulic jack at the lowest part of the billet, as shown in figure 13. For each tests the level of horizontal load was kept constant whereas the level of vertical load and vertical displacement of the billet varied from the minimum to the maximum levels (section 2.1. steps d and e). For every vertical load variation two different levels of horizontal load (H) was checked, either horizontal load equal to zero (H=0) or horizontal load equal to H=400KN for CHA Type-4 or H=280KN for CHA Type-2., This combination of vertical and horizontal forces have been applied for all structural formations (with or without dampers).

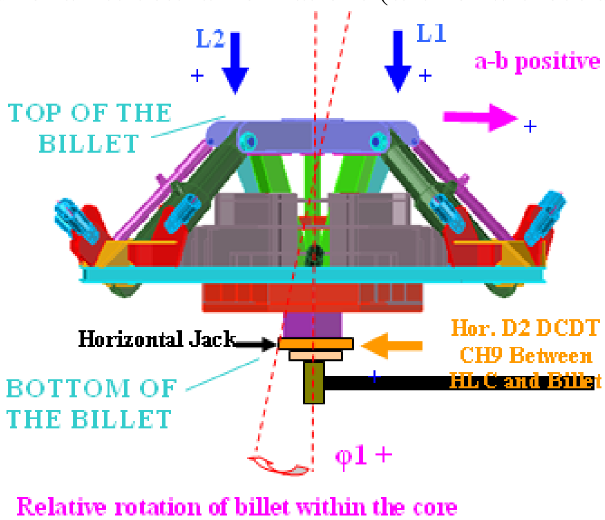


Figure 13. Imposed rotation of the billet relative to the hollow steel cylinder of the horizontal frame through the application of the appropriate horizontal load.

c1) The vertical load (V) / vertical billet (δ_v) displacement that was applied through the vertical hydraulic jack was applied in two different ways. First, this vertical displacement was applied in a continuous non-stop manner from the minimum to the maximum level and then after a brief stop back to the minimum level. Secondly, the vertical load (V) / vertical billet (δ_v) displacement was applied in 20mm vertical displacement intervals from the minimum to the maximum level and then after a brief stop back to the minimum level again in 20mm vertical displacement intervals.

The above parametric variation in the way the vertical load (V) / vertical billet (δ_v) displacement was applied was tried in combination with the variation of the previous two parameters; that is with or without the two dampers and with or without the horizontal H. This parametric variation was done together with the requirement to check the repeatability of the observed performance for each combination by performing at least three identical tests for each combination. This resulted in a large number of tests and in a similar large number of corresponding measurements.

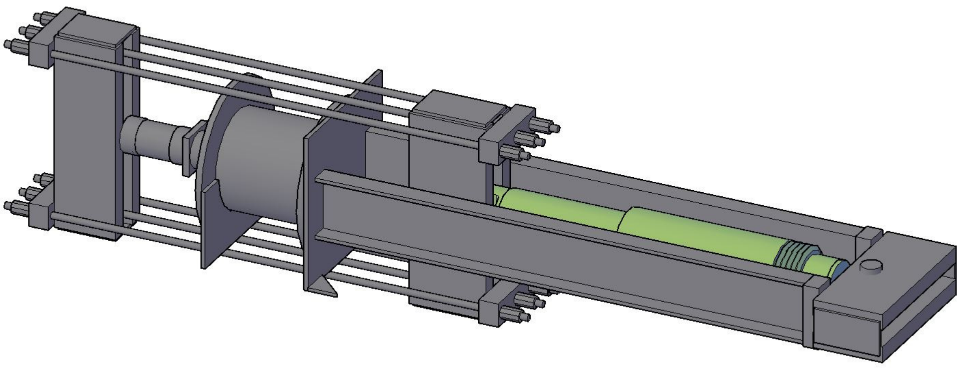
2.3 Instrumentation scheme

In order to measure the response of the various parts of the tested prototype suspension device specimens at the laboratory a number of load and displacement sensors were attached on the specimens that were continuously recording during testing. The vertical and the horizontal load were measured at the location where they were applied at the bottom of the billet level (figure 13). Moreover, the vertical displacement of the sliding billet relatively to the surrounding hollow cylinder (and the horizontal steel frame) was measured with three vertical displacement sensors that were fixed at the upper billet level (figure 3). The rotation of the billet relatively to the hollow steel cylinder was measured in two independent ways. First, by the differences recorded in the measurement of the vertical displacement of the billet relatively to the surrounding hollow steel cylinder as these vertical displacement sensors were fixed in three different places at the periphery of the billet's upper level. Secondly, by installing horizontal displacement transducers that measured the horizontal displacement of the billet relative to the hollow steel cylinder in two perpendicular directions at both the bottom billet level as well as at the top billet level. Apart from this instrumentation that is very essential to understand and describe the important behavioral characteristics of the performance of the CHA specimens additional instrumentation was also provided in order to che proper operation of the experimental facility especially that of the supporting reaction frame. For this purpose, additional displacement transducers were installed in order to ensure that the CHA specimens were practically fixed at their four supports; in addition, strain gauges were also installed on the pre-stressing bars in order to get the proper warning in the case of an accidental overstress of these pre-stressing rods in transferring the forces that developed on the suspension device during testing.

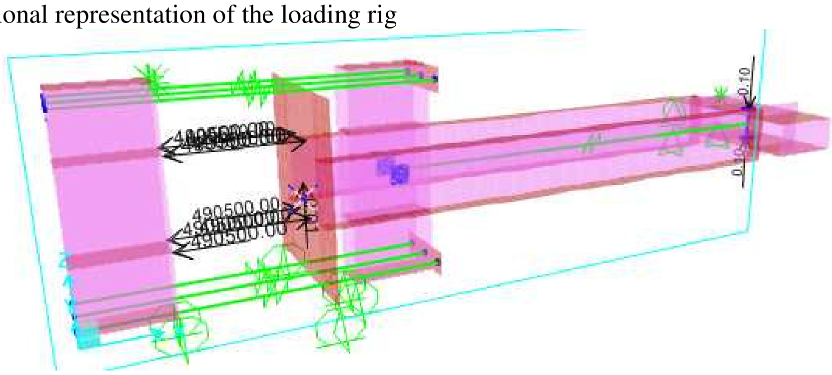
3 DESIGN AND CONSTRUCTION OF A LOADING RIG FOR TESTING THE INDIVIDUAL SPRINGS.

The tests of the full Column Head Assembly units (suspension devices), either Type-4 or Type-1, were complemented by a sequence of tests of every individual spring and damper that formed these CHA specimens. More than one hundred spring of the same type will be employed in the suspended roof of the Stavros Niarchos Cultural Center. In order to test the performance of these springs at the laboratory prior to their being used in-situ a special loading arrangement was manufactured at the laboratory of Strength of Materials and Structures of Aristotle University. A numerical simulation of this loading arrangement was built prior to the actual manufacturing in order to check its design and its expected performance. In what follows the basic steps of the design of the loading rig for these springs are briefly described together with the numerical simulations that were employed as part of this design process that led finally to the construction of this loading rig in the laboratory.

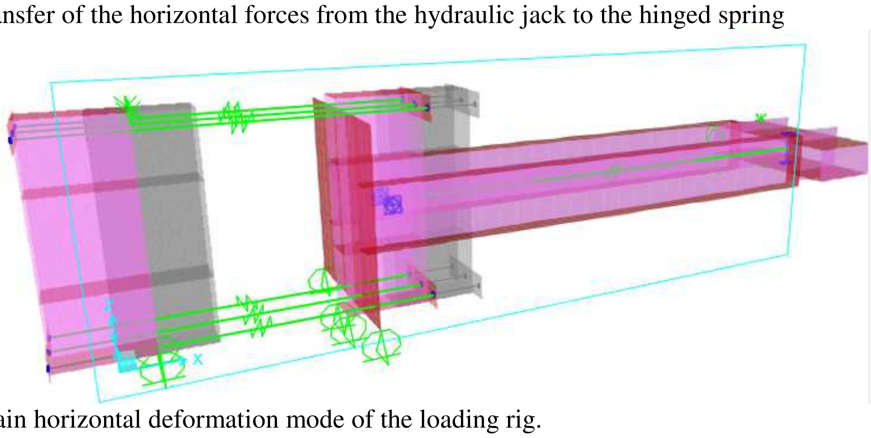
These springs have a maximum tensile capacity of two hundred tons and a corresponding extension in their length of 300mm. Their initial length is approximately 2.0m and their cylindrical part has a diameter of approximately 200mm. This paper presents the most interesting parts of this simulation together with the actual capabilities of this loading arrangement during the stiffness testing of the described springs. The numerical simulation of this loading rig is depicted in figure 14. It is formed of two basic parts. The first is formed by two horizontal UPN320 steel sections that are joined together at the right end by a stiff horizontal steel block whereas they are joined together in the front with a vertical steel plate that also forms the basis of hydraulic jack (figure 14a). To the left of the hydraulic jack in figure 14a the load cell measuring the applied load is located. Through this loading cell the far left end vertical steel rigid block is forced horizontally towards the left. This steel block is connected with pre-stressing rods with a similar rigid steel block that is placed at the middle of the loading rig between the UNP320 steel sections. The spring to be tested in axial extension is hinged in this steel block (green colour) as well as in the steel block at the far right of the loading rig. When the hydraulic jack is extended horizontally outwards from right to left it also forces the far left rigid steel block and through the pre-stressing rods the middle steel block. Thus, the spring that is secured between the middle and the far right steel blocks is appropriately extended by a similar amount of horizontal displacement. The force that is required for this horizontal extension of the spring depends upon the stiffness properties of the tested spring and it is provided by the hydraulic jack because the vertical rigid blocks are sliding horizontally in unison providing almost zero horizontal resistance.



a) Conceptional representation of the loading rig



b) The transfer of the horizontal forces from the hydraulic jack to the hinged spring

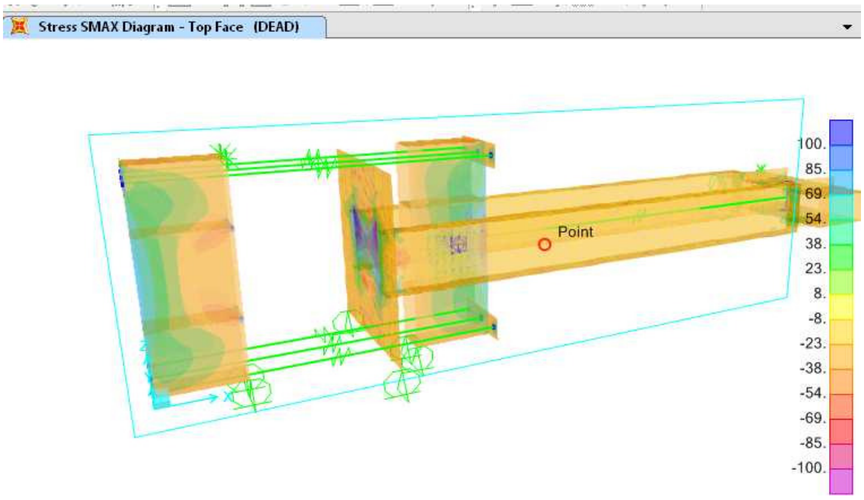


c) The main horizontal deformation mode of the loading rig.

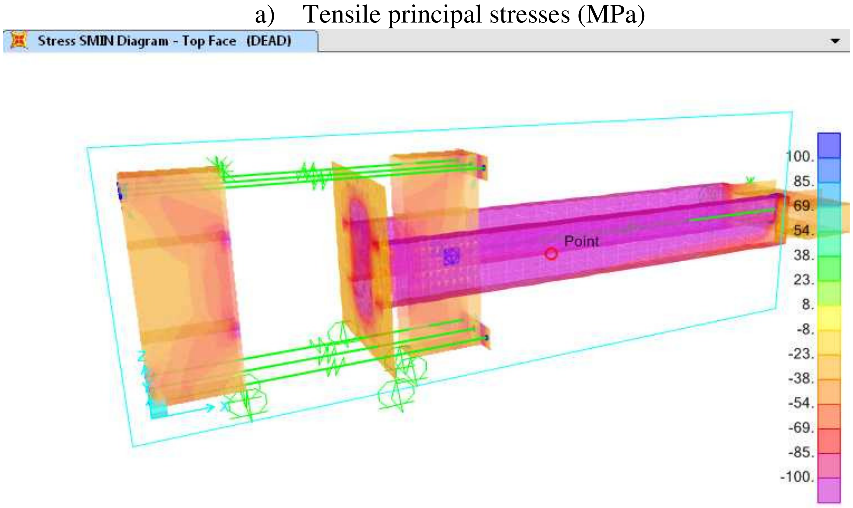
Figure 14. The concept of the loading rig and its numerical simulation

3.1 Static numerical analysis results

The numerical analyses results helped to identify the level of stresses that developed at the various parts of this loading rig and facilitate in this way its design and construction. Typical results are shown in figures 15a and 15b that depict the maximum (tensile) and minimum (compressive) axial stresses in MPa, respectively, that develop in the various steel parts of the loading rig for the maximum applied horizontal load of 2000KN (figure 14b). From the numerical analyses it could be seen that the most stressed parts are the two UPN320 steel sections in compression.



a) Tensile principal stresses (MPa)

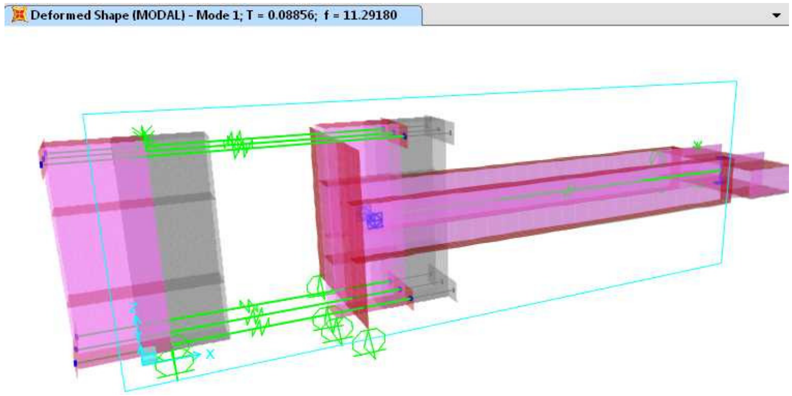


b) Compressive principal stresses (MPa)

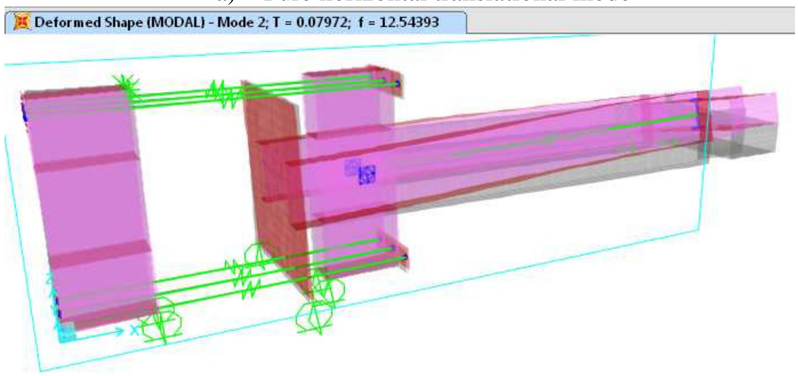
Figure 15. Axial stress distribution for the maximum horizontal load condition of 2000KN

3.2 Modal dynamic numerical analysis results

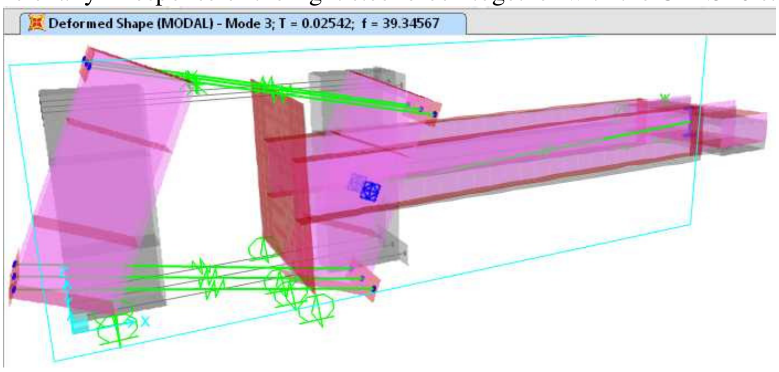
In this section the modal analysis results will be briefly presented and discussed. As part of the testing sequence was to test the spring in dynamic loading with a frequency of 0.75Hz the modal dynamic numerical analyses were aimed to understand the fundamental modes of vibration of this loading rig.



a) Pure horizontal translational mode



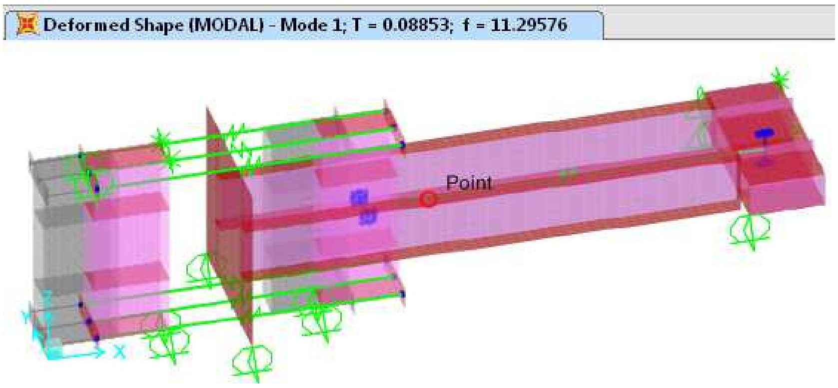
b) Torsional y-z response of the right steel block together with the UPN320 steel sections



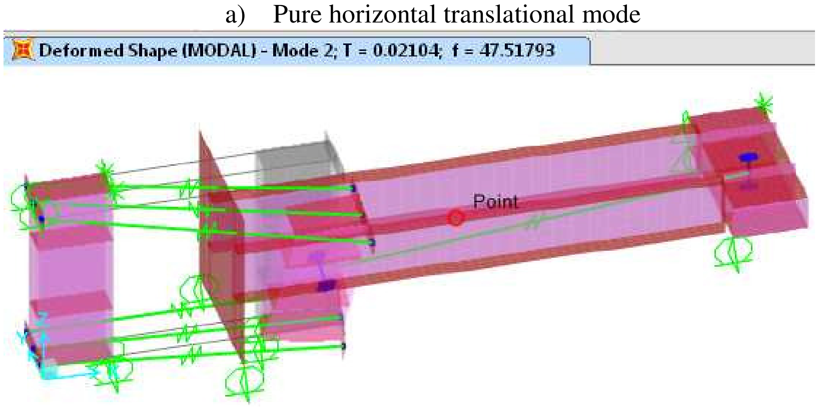
c) Rotational x-z response of the far left and middle steel blocks joined with the pre-stressing rods.

Figure 16. First three modes of vibration of the loading rig.

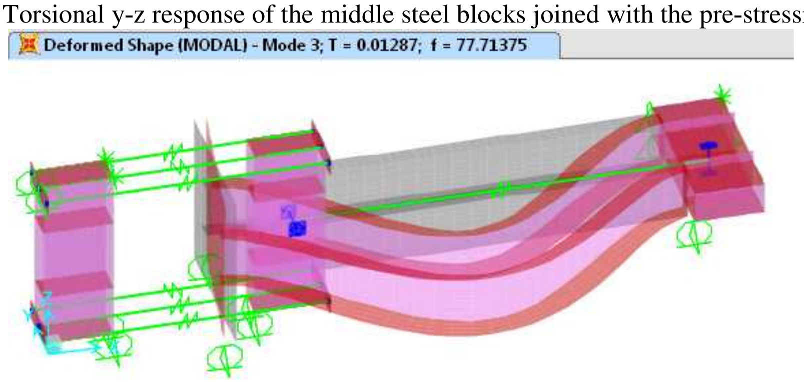
The first fundamental modes of vibration are depicted in figure 16a, b and c. It can be seen that the fundamental mode of vibration that is the pure horizontal translational mode, which coincides with the main displacement pattern that this loading rig is designed to be utilized during testing, is for an eigen-frequency equal to 11.292Hz which is a much higher value than the excitation of 0.75Hz that is the dynamic testing frequency. Moreover, the next two modes of vibration although at high frequencies demonstrate a tendency of the loading ring to deform in torsional and rigid body rotational modes that can be considered as undesired for the main testing objectives of this loading rig. An effort was made to prohibit these undesired modes of vibration by adding a minimum number of support restrains. These restrains were also materialized in the construction stage of this loading rig. Initially, a support was added at the far right steel block (see figures 16a and 17a) in order to prohibit the previously observed torsional response (figure 16b). Next, additional supports were added at the far left block prohibiting its x-z rotational response.



a) Pure horizontal translational mode



b) Torsional y-z response of the middle steel blocks joined with the pre-stressing rods.

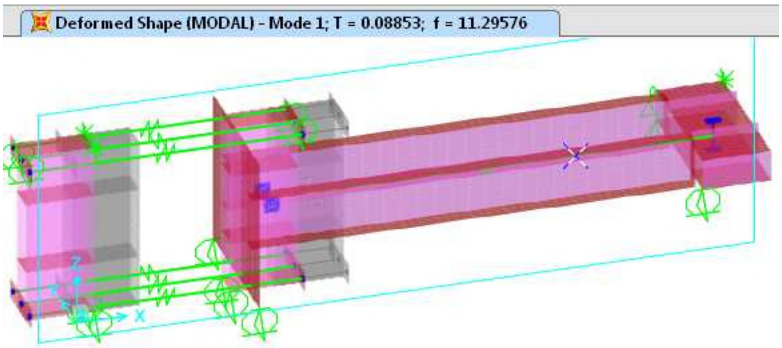


c) Non-symmetric buckling mode of the UPN320 steel sections

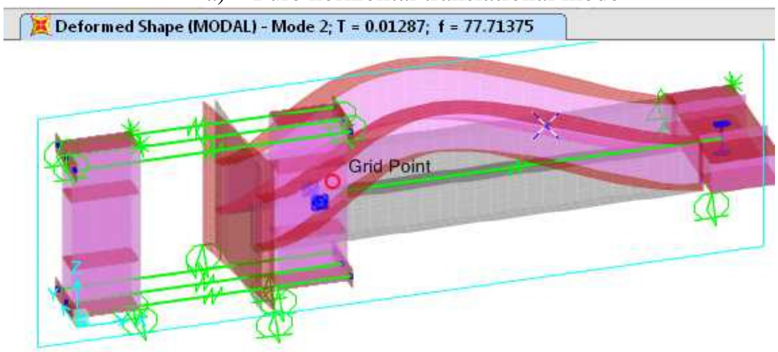
Figure 17. First three modes of vibration of the loading rig.

The first fundamental modes of vibration this time are depicted in figure 17a, b and c. It can be seen that the fundamental mode of vibration that is the pure horizontal translational mode, which coincides with the main displacement pattern that this loading rig is designed to be utilized during testing, remains almost unchanged with an eigen-frequency equal to 11.296Hz which again is a much higher value than the excitation of 0.75Hz that is the dynamic testing frequency. The next mode is a y-z rotational response of the middle steel block whereas the third mode is a buckling flexural mode for the double UPN320 steel sections. These later eigen-modes have relatively very high eigen-frequency values (47Hz and 77Hz).

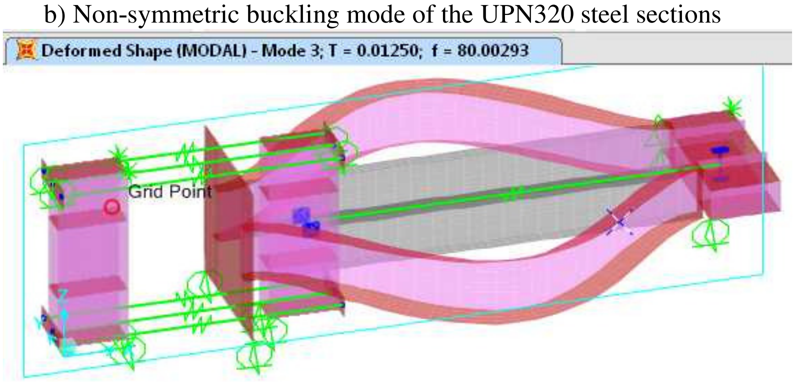
Again, an additional effort was made to prohibit the second mode of vibration by adding again some extra restrains in the middle steel block. The corresponding modal analysis results are depicted in figures 18a, b and c.



a) Pure horizontal translational mode



b) Non-symmetric buckling mode of the UPN320 steel sections

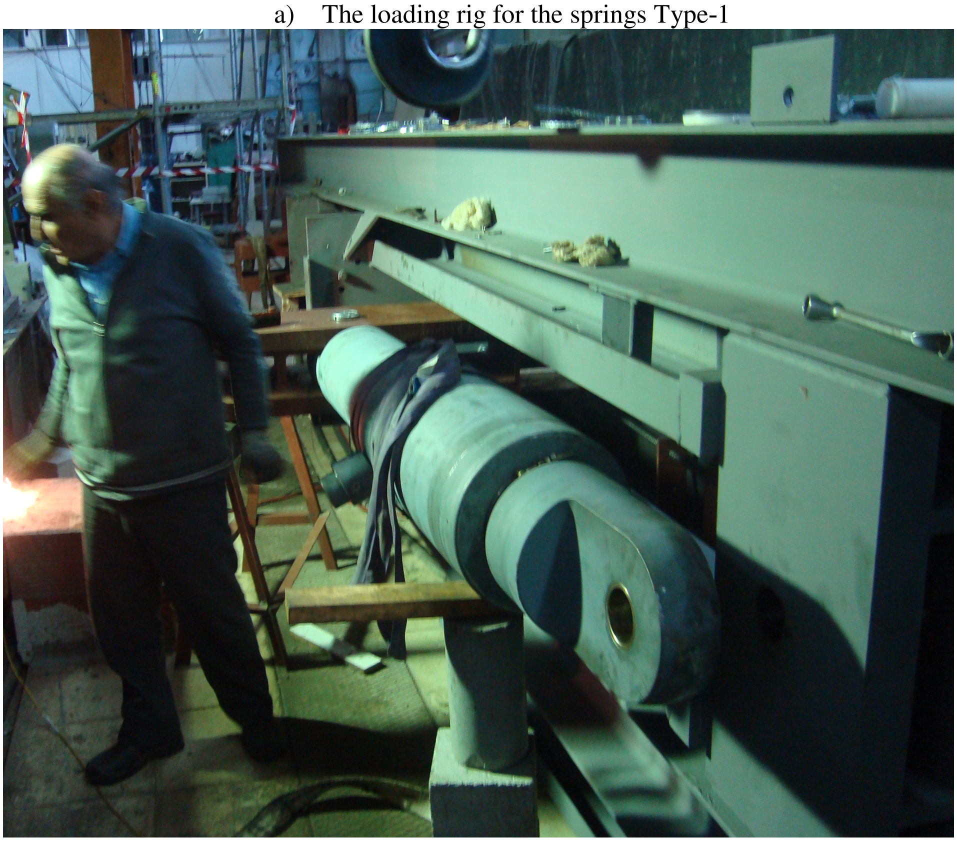


c) Symmetric buckling mode of the UPN320 steel sections

Figure 18. First three modes of vibration of the loading rig.

It can be seen that the fundamental mode of vibration that is the pure horizontal translational mode, which coincides with the main displacement pattern that this loading rig is designed to be utilized during testing, remains almost unchanged with an eigen-frequency equal to 11.296Hz which again is a much higher value than the excitation of 0.75Hz that is the dynamic testing frequency. The rigid body rotational modes are prohibited. Instead, the next two eigen-modes of vibration are the non-symmetric and the symmetric buckling flexural modes of the double UPN320 steel sections. These later eigen-modes have relatively very high eigen-frequency values (77Hz and 80Hz). As already mentioned before, certain measured were taken in the construction process to insure that these undesired modes of torsion or rigid body rotation were prohibited. The finished loading rig is depicted in figure 19.

a) The loading rig for the springs Type-1

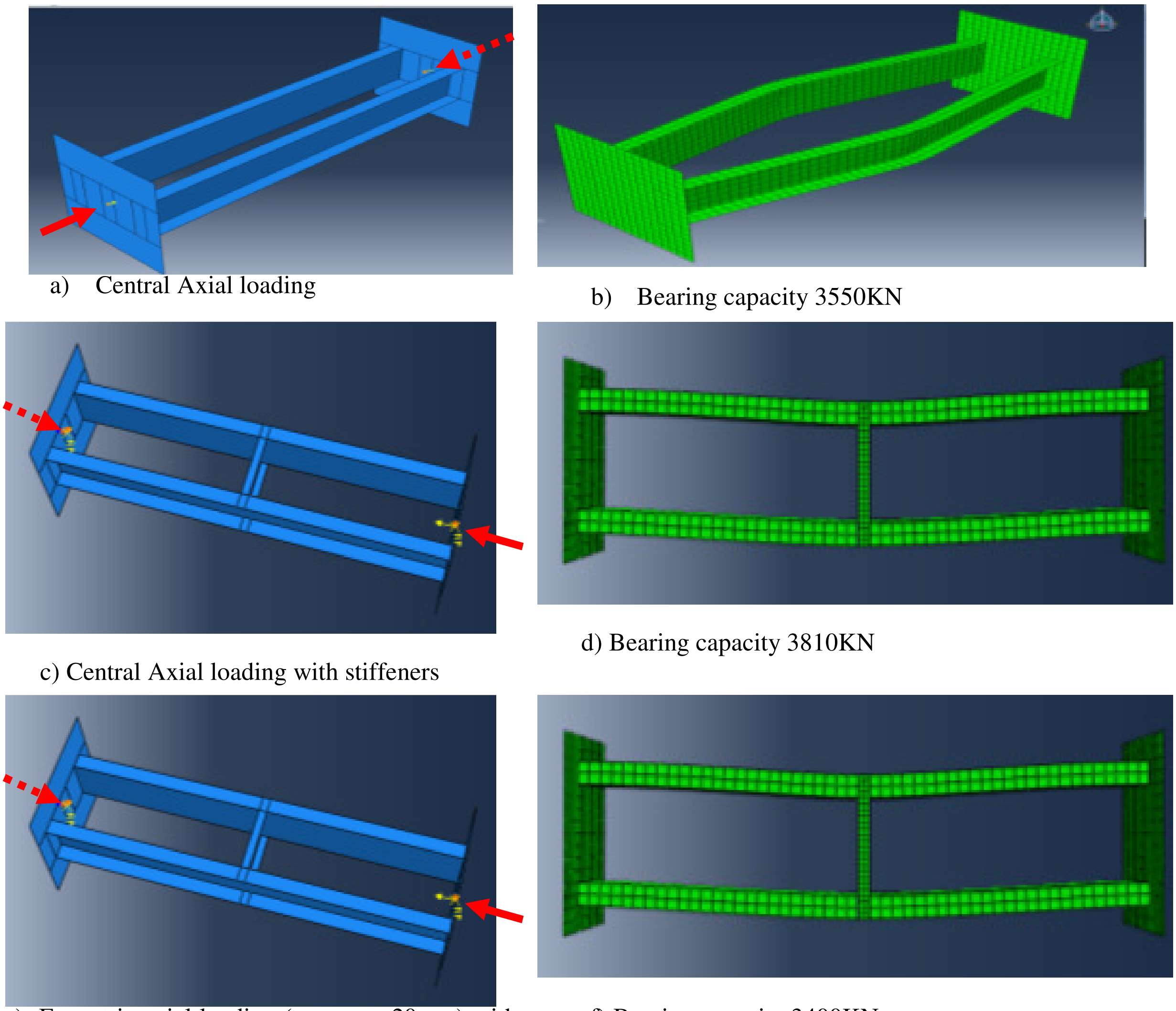


b) Placing a Type-4 spring in the loading rig for testing

Figure 19. The loading ring for the springs during testing

3.3 Static non-linear analysis to identify the bearing capacity of the UPN320 steel cross-sections.

As shown in sections 3.1. and 3.2. the UPN320 steel cross-sections develop considerable compressive stresses for the maximum test load that are of the order of 140MPa. In addition, the modal analysis results demonstrated that the non-symmetric and the symmetric modes of vibration are the two modes expected to develop in the system after the pure horizontal translational mode, when the torsional and rotational modes are prohibited with the proper restraining. In order to investigate the bearing capacity of the loading rig against this type of buckling an additional numerical simulation was performed. In all these numerical simulations the actual dimensions and mechanical properties of the steel cross-sections were employed. Moreover, both end supports were considered to be hinged. Initially, the two UPN320 sections were joined together only at their ends. Next these two steel cross sections are joined at mid-span with two steel stiffening steel plates with dimensions 600mm x 50mm and 5mm thick, that were placed at either side as shown in figure. The non-linear numerical analyses were performed utilizing the capabilities of the ABAQUS commercial software package ([3], [4]). As can be seen in figures 20b and 20d the buckling bearing capacity is equal to 3550KN in the case without the stiffeners and increases to 3810KN when the described stiffeners are put in place. When these buckling bearing capacity values are compared with the target axial load of 1900KN a safety factor value is found equal to 1.868 and 2.005 for the case without and with the stiffeners, respectively



a) Central Axial loading

b) Bearing capacity 3550KN

c) Central Axial loading with stiffeners

d) Bearing capacity 3810KN

e) Eccentric axial loading ($e_x = e_y = 20$mm) with stiffeners

f) Bearing capacity 3400KN

Figure 20. Numerical simulation results of the buckling bearing capacity

Finally, the last case with the stiffeners is numerically simulated again; this time, however, the axial load is applied with an accidental eccentricity in both the x and y direction equal to $e_x = e_y = 20$mm. The bearing buckling capacity this time is found equal to 3400KN that corresponds to a safety factor value equal to 1.789.

All these safety factor values ensure the safe performance of the described testing rig. This designed loading rid was constructed and was successfully utilized for all the

4 CONCLUSIONS

- The basic loading functions of the suspension system of the roof deck that is to be constructed at the Stavros Niarchos Foundation Cultural Center is briefly described as well as how this was simulated at the laboratory of Strength of Materials and Structures of Aristotle University in order to measure the performance of prototype suspension device specimens prior to being installed in-situ.
- Each one of these suspension devices (Column Head Assemblies) is composed of a steel rigid frame that has in its center a hollow steel cylinder that hosts a sliding billet. In addition there are four springs and two dampers that are hinged at their bottom end to the rigid steel frame and at their top to the sliding billet. Apart from testing the performance of the Column Head Assembly specimens the performance of the prototype springs and dampers that form these suspension devices were also tested in the laboratory.
- A special loading rig was designed and finally constructed to be utilized in the prototype testing of the performance of the springs.
- A series of linear and non-linear numerical simulations were employed towards securing the safe performance of this loading rig during the testing of the said springs.

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