SEISMIC PERFORMANCE OF A PRECAST ELEMENT CONTINUITY CONNECTION SYSTEM

Angela Saviotti, Department of Structural and Geotechnical Engineering,
Sapienza University of Rome, Rome, Italy
Pierluigi Olmati, Department of Structural and Geotechnical Engineering,
Sapienza University of Rome, Rome, Italy
Luca Sgambi, Department of Structural Engineering
Politecnico di Milano. Milan, Italy
Franco Bontempi, Department of Structural and Geotechnical Engineering,
Sapienza University of Rome, Rome, Italy

ABSTRACT

The past experiences about earthquakes have shown that reinforced concrete structures are prone to be subject to beam-column joint failure. Connections are one of the most essential parts especially to precast concrete structure. Connections transfer forces between precast members, so the interaction between precast units, is obtained at a system level. An acceptable performance of precast concrete structure depends then especially on the appropriate kind of connections choice: adequate detailing of components and design of the connections is fundamental.

In general terms, it is interesting to study the behavior of connecting elements and to compare different solutions of ductile connections for precast concrete structures in case of horizontal applied force as well as those produced by earthquake situation, while also furthermore considerations about the structural robustness can be carried out.

In this paper the mechanical behavior of a specific beam-column connection is examined by a finite element analysis developed by DIANA® commercial software, where the modeling of the nonlinear behavior of both the concrete and the mortar is made by a total strain crack model while a bilinear plasticity model is considered for the reinforcing steel.

The full load capacity of the connection is developed, considering both the presence and the absence of a mortar stratum, devoting specific attention to the crack pattern development. Due to the complexity of the analysis, an independent model developed by the Code ASTER® research code is compared with the previous one.

Keywords: Structural connections, Precast concrete structures, Seismic design, Finite Element Analysis, Ductility.

INTRODUCTION

This work is aimed to model and analyze the mechanical behavior of beam-column precast concrete structures where an innovative ductile connection system is introduced.
The beam-column joints represent the most delicate part of a structure [1, 2]. From the selection of the connection system and its correct sizing, it depends the response to the actions that the structure is subjected.
To develop the study, at first the analysis is conducted by a 2D Model while in a later stage the structure was represented through a 3D model.
In both cases, the study has focused on a comparison between a model, named Model A, in which there is the presence of a link layer of mortar between beams and column and a model, named Model B, in which the mortar stratum is absent.
The analysis is performed using the finite element program DIANA® [3]: regarding the geometry, the discretization and the extrapolation of the results were conducted by a pre- and post-processor called Midas + Fx specific for DIANA®.
The non-linear mechanical behavior of the concrete is considered using the Total Strain Crack Model while for the steel the Von Mises failure criterion is adopted.
Topical issue for the structural connection is without doubt the behavior under seismic loadings. For this reason, the load condition that has been studied is based on the application of a horizontal force at the top of the column.
Analysis has shown how it is possible to develop the full capacity of the connection devices without a large failure of concrete and mortar: then, the connection system has been well conceived with a regular progressive formation of cracks in the concrete.
An important result, in view of sensitivity analysis necessary due to the complexity of the finite element model, is without doubt the similarity between response curves obtained with the program DIANA® and the ones obtained with the Code ASTER® [4].
From the design point of view, one important point is the role that assumes the layer of mortar: in fact it contributes to increase both the initial stiffness of the structure and the final global strength.
Finally the results confirmed the soundness of the introduction of this innovative ductile connection system: in this case the concern has been about the possible presence of brittle fracture in concrete. This occurrence is denied from the results, and quite smooth and regular behavior was obtained, with consistent and developed plastic strains in the bars, as confirmation of the realization of a system in all respects ductile.

CONNECTION DESIGN DETAILS

In this study, a quite innovative ductile connection system for the beam-column connection is considered: Figures 1-2 show the layout and details of studied structure.
The beams have a length of 3770 mm from the face of the column to the end section of the beam. The column has a height of 4700 mm. The beams and the column are reinforced with longitudinal and transverse reinforcement. Mortar is placed in the vertical joints and a rubber pad is placed on the upper surface of the corbel.

The column section is 800 x 600 mm (Fig. 2b). All the longitudinal reinforcing steel in the column has 22 mm diameter and the vertical stirrups in the column have 8 mm diameter and a space ranging from 50 mm to 86 mm.

The beam has a T-down section, with largest base of 900 mm and height of 250 mm and smaller basic of 500 mm and height of 350 mm (Figure 2.a). All the longitudinal reinforcements in the beams have 35 mm diameter. The vertical stirrups in the beam end have 8 mm diameter and a spacing of 50 mm. The stirrups away from the interface have 8 mm diameter and a spacing of 100 mm.

The corbel section is 300 x 500 mm; its longitudinal reinforcement has 22 mm diameter and its cross reinforcement has 8 mm diameter and a spacing of 50 mm.

The specific system of connection between beam and columns is shown in Figure 3.

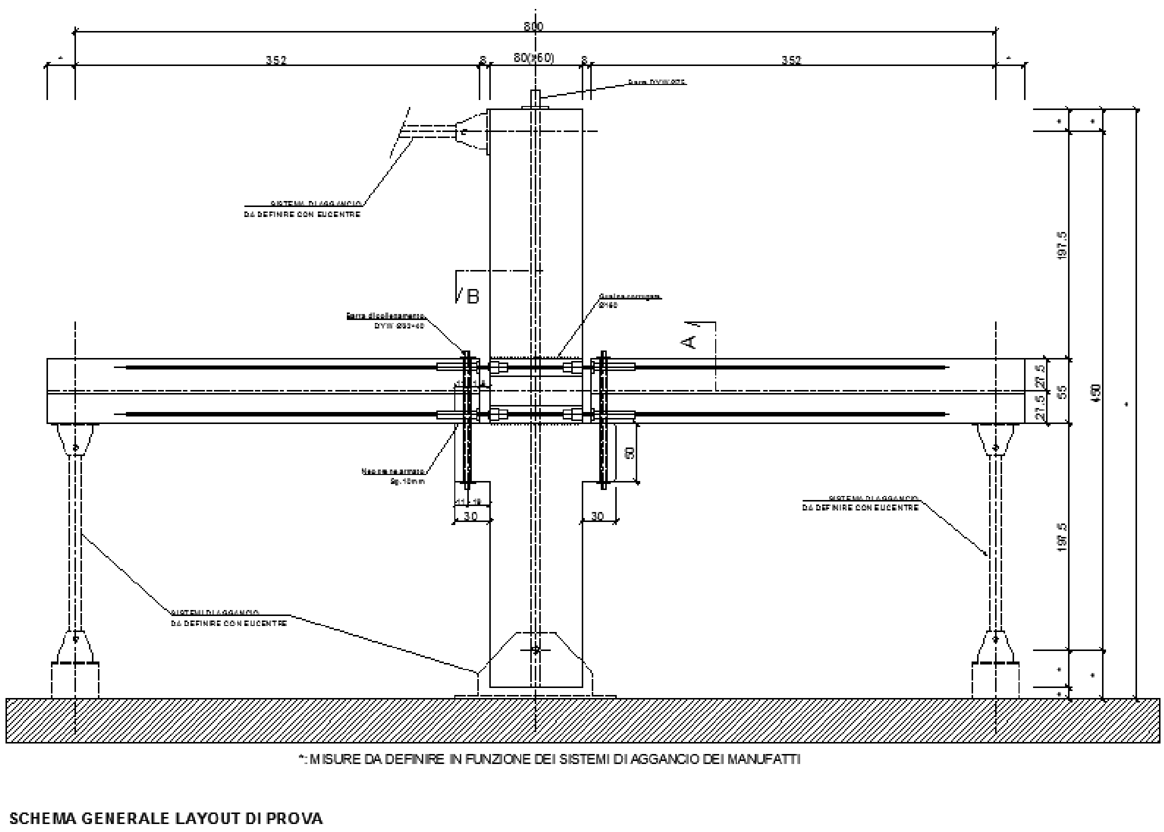


Figure 1 - General layout of the test pattern.

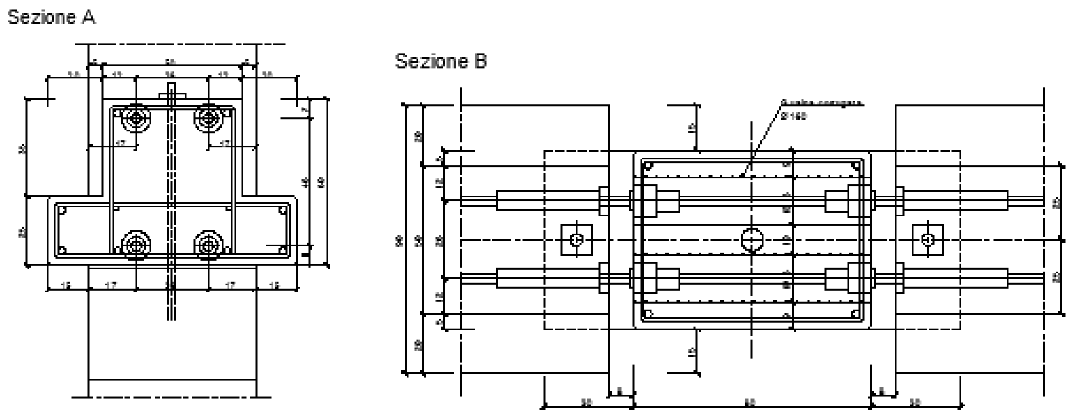


Figure 2 – Details of the beam section (left) and of the column section (right).

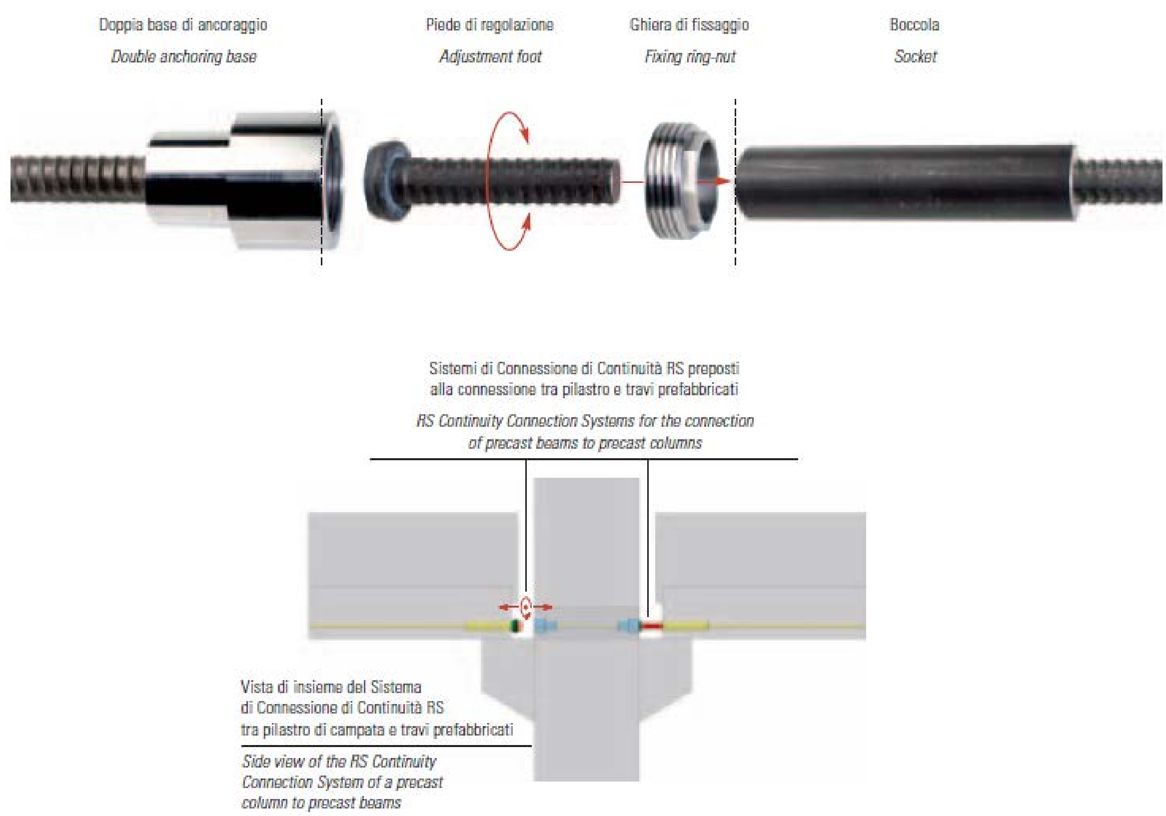


Figure 3 – Details of the generic bar used in the beam-column innovative ductile connection system.

MATERIALS COSTITUTIVE MODELS

In this work, different constitutive materials models for the different parts of the beam-column sub assemblage are considered. Particular attention was devoted to the passage from linear models to nonlinear constitutive formulations both to gain confidence on the numerical results and to catch specific forma of damage or plasticization.

Table 1 shows the kind of constitutive behavior of material chosen and the combinations with which they were used in the Model A (with mortar stratum between beam and column) and in the Model B (without mortar stratum).

Table 1.

	STEEL		CONCRETE			
			Compressive Behavior		Tensile Behavior	
	Linear Elasticity	Ideal Plasticity	Linear Elasticity	Ideal	Linear Elasticity	Tension Softening curve based on fracture energy
A1	X		X		X	
B1	X		X		X	
A2.1		X	X		X	
B2.1		X	X		X	
A3.1	X			X		X
B3.1	X			X		X
A4.4		X		X		X
B4.4		X		X		X

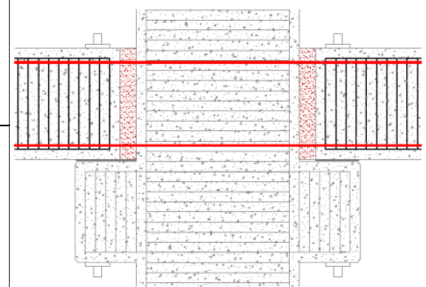
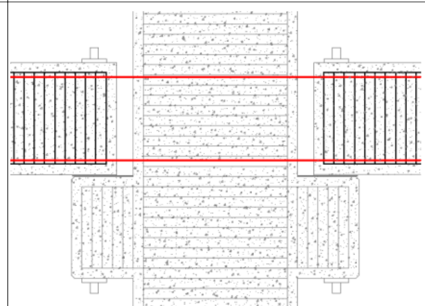
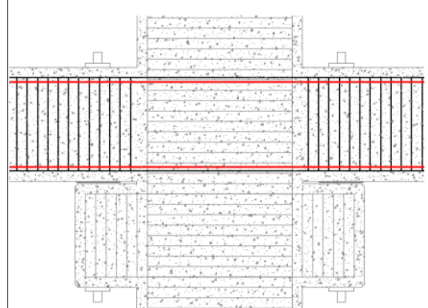
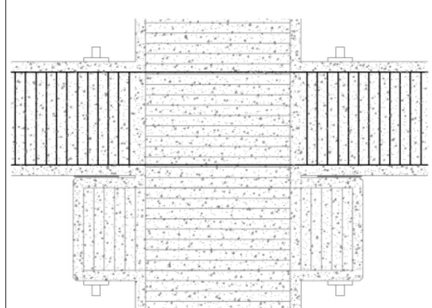
Briefly, the hierarchy of models developed comprises:

- models “A1” and “B1” have linear elastic constitutive behavior of materials;
- the constitutive relationship for materials of models “A2.1”, “A2.2”, “B2.1”, “B2.2” is nonlinear for steel and it is linear elastic for concrete;
- the constitutive behavior of materials for models “A3.1”, “B3.1” is nonlinear for concrete and it is linear elastic for steel;
- finally, the models “A4.4”, “B4.4” have implemented a nonlinear behavior both steel that concrete.

In Table 2, a summary of the studied cases is shown.

The cases differ then in the materials of the connection stratum between beam and column and in the arrangement of the reinforcements. The models “A4.4 monolithic”, “C1” and “C2”, they represent the situations in which the connection stratum is made by the same concrete of the beams and column: so, the structural system can be considered monolithic, and for these models, only the nonlinear analysis is made.

Table 2.

		BEAM	COLUMN	STRATUM	REINFORCEMENT
A	A1 A2.1 A3.1 A4.4	CONCRETE	CONCRETE	MORTAR	
	A4.4 monolithic	CONCRETE	CONCRETE	CONCRETE	
B	B1 B2.1 B3.1 B4.4	CONCRETE	CONCRETE		
C	C1	CONCRETE	CONCRETE	CONCRETE	
	C2	CONCRETE	CONCRETE	CONCRETE	

A concrete C40/50 and a Steel B450C were chosen and in Table 3 a synthesis of materials parameters is shown.

Table 3.

CONCRETE C40/50		STEEL B450C	
f_{ck}	40 N/mm^2	f_{Yk}	450 N/mm^2
R_{ck}	50 N/mm^2	f_{tk}	540 N/mm^2
f_{cm}	48 N/mm^2	E_y	206000 N/mm^2
f_{ctm}	3.51 N/mm^2	ν	0.3
f_{cfm}	4.21N/mm^2		
E_{cm}	35220 N/mm^2		
ν	0.2		
CONCRETE FOR STRATUM		**RUBBER**	
f_{cm}	28 N/mm^2	E_y	500 N/mm^2
f_{ctm}	1.547 N/mm^2	ν	0.4
E_y	30960 N/mm^2		
ν	0.2		

As said before, the behavior of the concrete is modeled with the total strain based constitutive Model which describe the tensile and compressive behavior of a material with one stress-strain relationship. The constitutive Model based on total strain is developed along the lines of the Modified Compression Field Theory, originally proposed by Vecchio & Collins [5, 6, and 7].

For the reinforcement, an elastic-plastic Model is adopted both in tension and compression, with Von Mises yield criterion. As known, this criterion is based on the determination of the distortion energy in a given material that is of the energy associated with changes in the shape in that material. For the steel a predefined class according to the NEN 6770 code was used.

TWO DIMENSIONAL MODELLING

In Midas Fx+ for DIANA®, for the two-dimensional modeling the following steps should be performed:

- definition of geometry,
- creation of mesh,
- assignment of materials,
- assignment of properties,
- introduction of boundary conditions,
- application of loads/displacements.

The creation of geometry in Midas Fx+ for DIANA® is made by entering the coordinates from external files (.txt) to create points and then connecting the dots to create poly-lines. After the formation of poly-lines, DIANA® can create surfaces directly.
About mesh, it is chosen a discretization more refined at the connecting joint between beam and column and a coarse mesh elsewhere. Regularity checks about the size and the forms of the finite elements were developed.

The resulting mesh is shown in Figure 10 a), b), c), and d).

A zoom of beam-column joint mesh is shown in the Figure 10 b and d: it's possible to view how in this area, the mesh is more refined that in the rest of the structure.

In Figure 10 e) and f) a layout is shown where it is possible to appreciate how the reinforcing steel is represented in DIANA®.

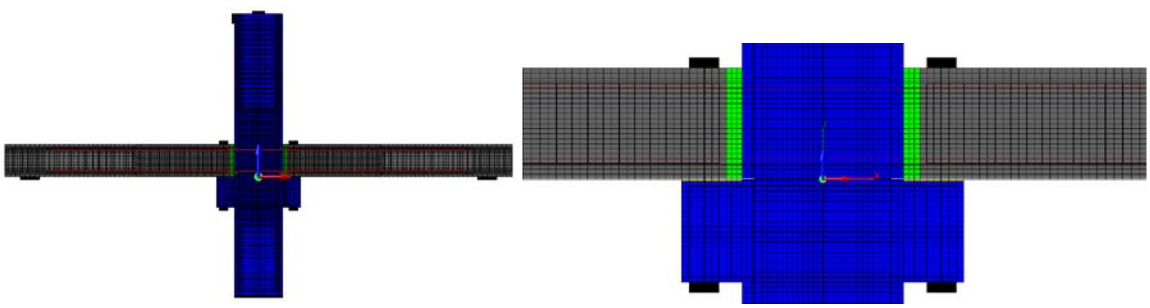


Figure 10 a) - Model A with connection mortar stratum; b) zoom of beam-column joint region.

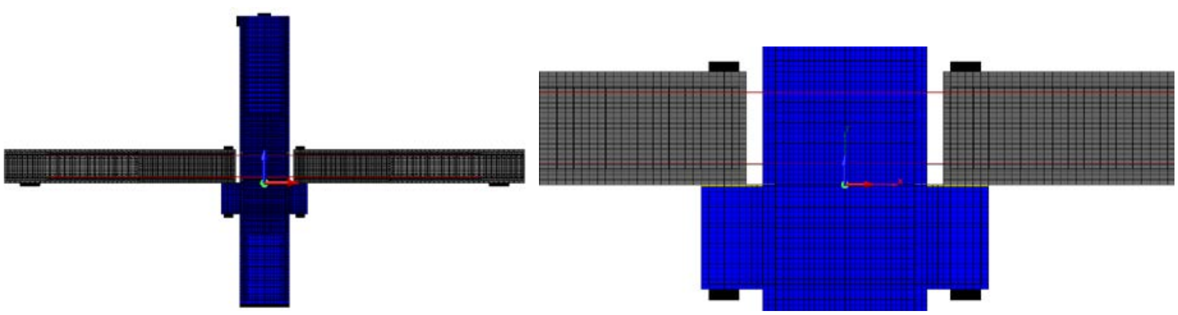


Figure 10 c) - Model A without connection mortar stratum; d) zoom of beam-column joint region.

.

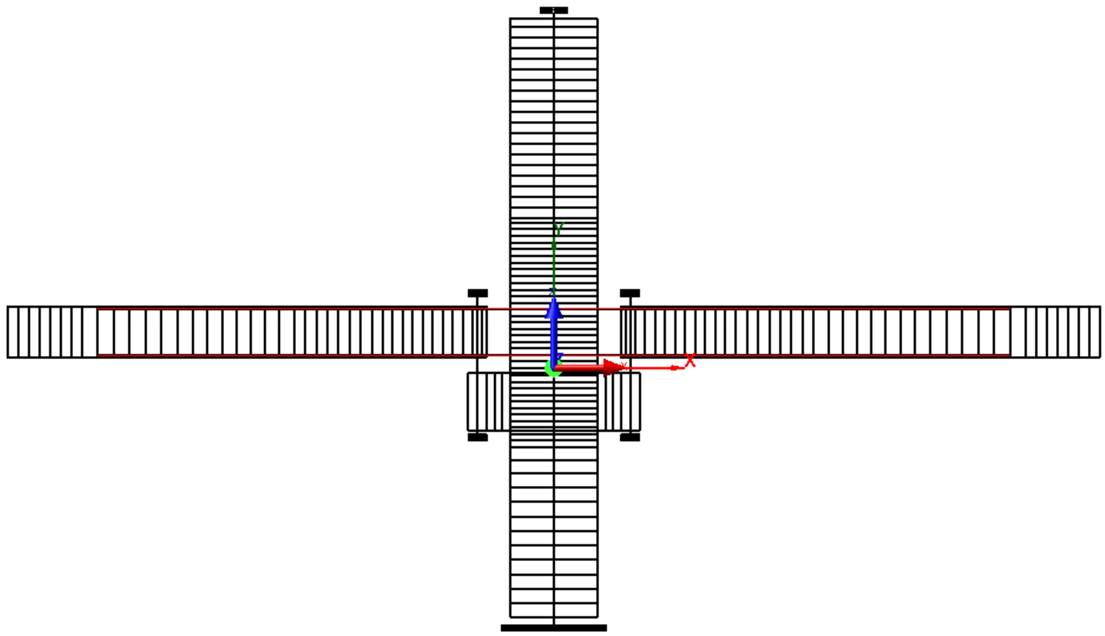


Figure 10 e) – Overall reinforcing steel layout.

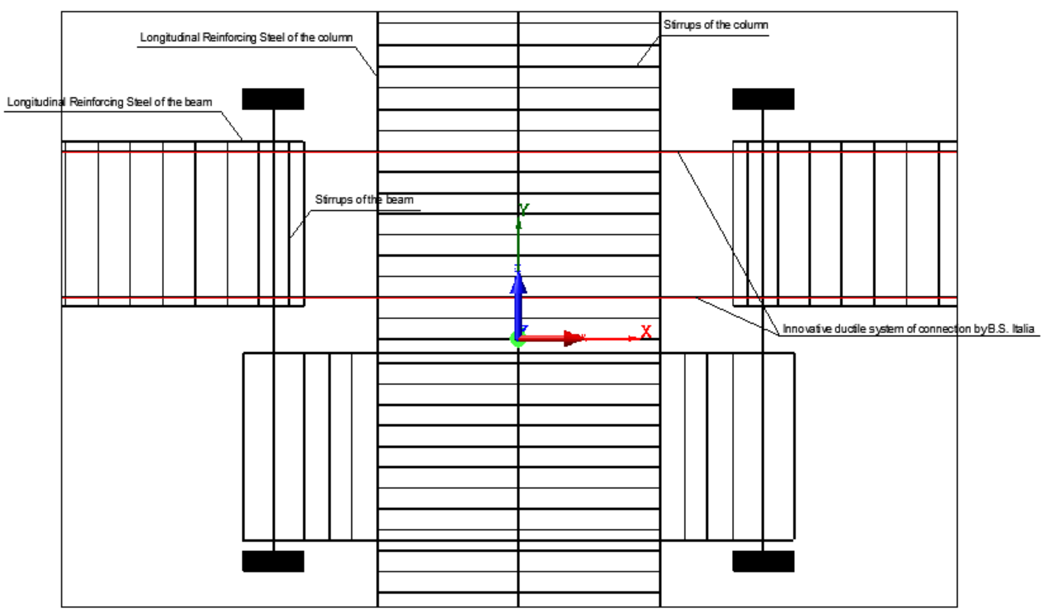


Figure 10 f) – Reinforcing steel layout: zoom of beam-column joint region.

As briefly mentioned before, the Midas Fx+ for DIANA® pre-/post-processor provides a feature that evaluates the mesh quality: it is an option that identifies elements that fail quality tests, which includes angles, angle aspect ratios, positioning of the midsize node for higher order elements and the extent of warping. After several tryouts the mesh passed all the quality tests, as shown by Figure 11.

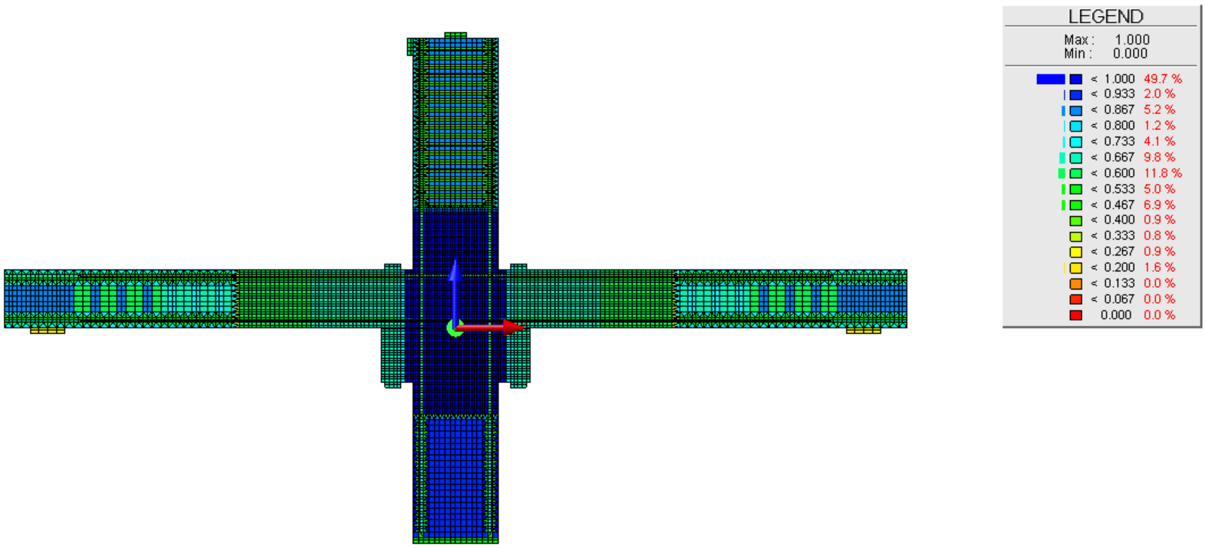


Figure 11 – Mesh quality control in Midas Fx+ for DIANA for Model A.

BOUNDARY CONDITIONS AND LOAD

In this work the structure under investigation have the beams fixed at the extremity by fixing the vertical motion of the beam supports. Instead the base of the column is fixed by fixing the horizontal motion of the column base support. Finally a vertical displacement is imposed at the top of the column, like shown in Figure 12.

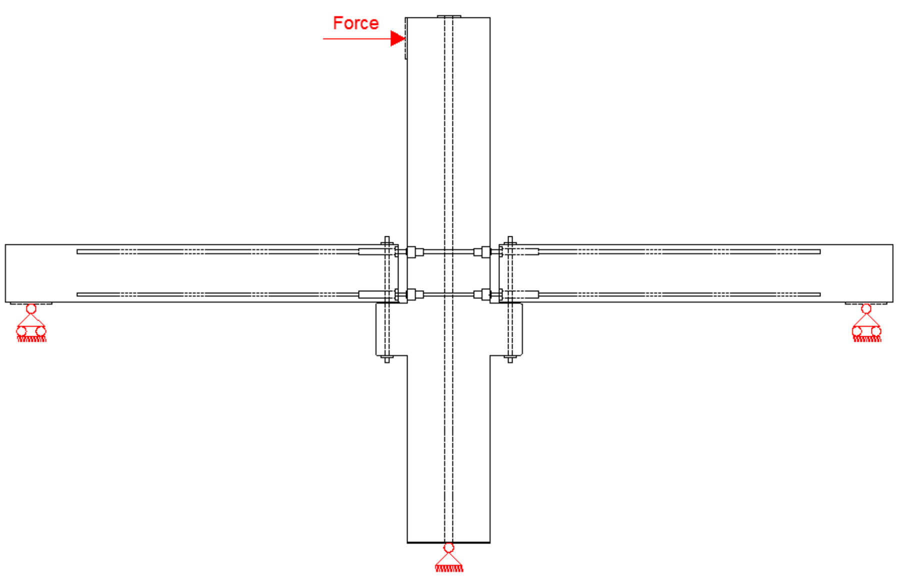


Figure 12 – Boundary conditions and applied horizontal loading force.

First, a linear analysis is performed in order to check the model. In this work the partial results of linear analysis about Model A and Model B is presented. After the analysis is done DIANA® checks whether any badly shaped elements exist. There were no such warning messages in the analysis-progress window or in the standard output file, and so it is possible to inspect and accept the analysis results: global results are presented in Fig.13, while detailed aspects are shown in Figures 14 - Model A - and 15 - Model B. Looking at pictures, it is clear the impact of the presence or absence of the mortar stratum.

In fact, with regard the σ_{xx} tensions (Figures 14.c and 15.c), the coupling devices elements of connection of the Model A have a σ_{xx} max of about $130 \mathrm{N/mm^2}$, while the devices system of connection of the Model B reach the σ_{xx} max of about $1580\ \mathrm{N/mm^2}$. Instead speaking about displacements (Figures 14.a and 15.a) the application of horizontal load of 600 kN at the top of the column of Model A causes an highest displacement of 23.4 mm while in case of Model B it produces an highest displacement of 35.1 mm.

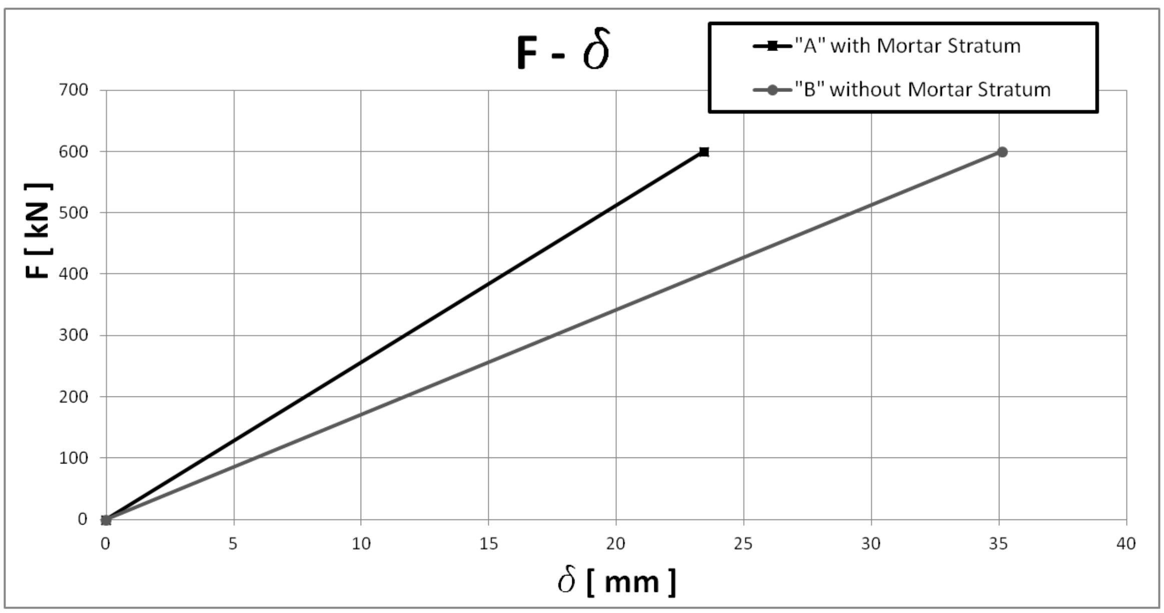


Figure 13 – Linear analysis results: Model A vs. Model B.

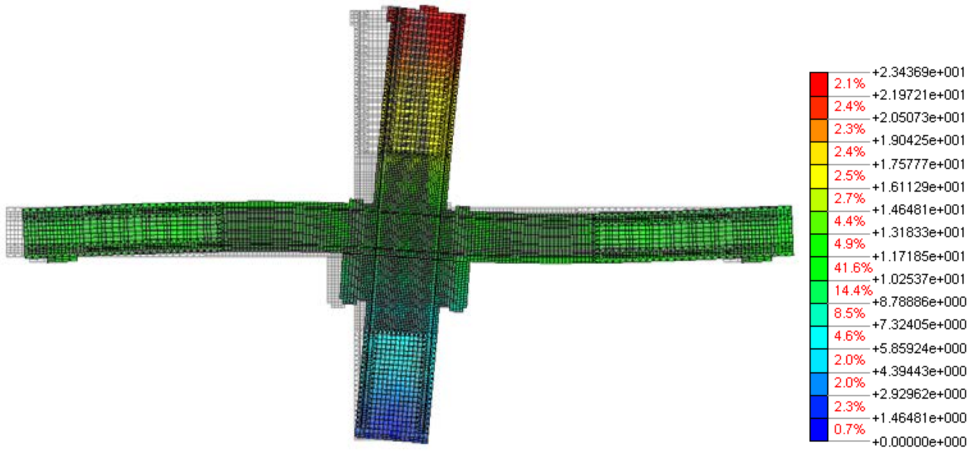


Figure 14 a) - Model A: displacement caused by application of horizontal force of 600 kN at the top of the column.

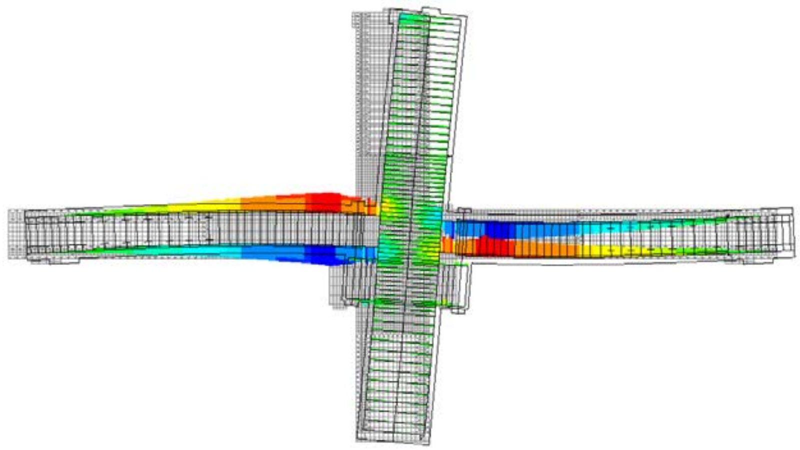


Figure 14 b) –Model A: stress in x-direction for load of 600 kN that it was applied at the top of the column.

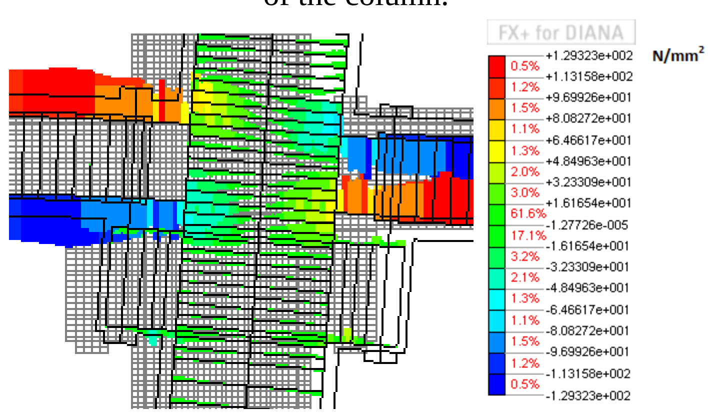


Figure 14 c) – Model A: zoomed view of stress in x-direction for a load of 600 kN applied at the top of the column.

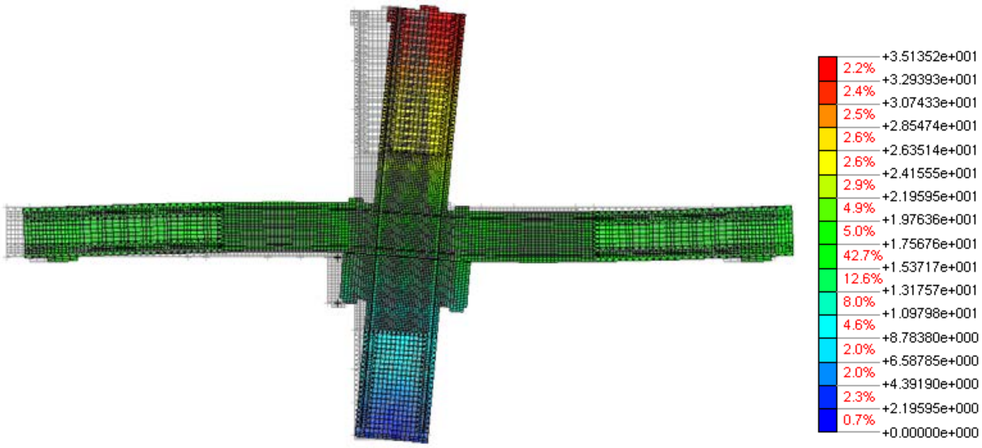


Figure 15 a) –Model B: Displacement caused by application of horizontal force of 600 kN at the top of the column.

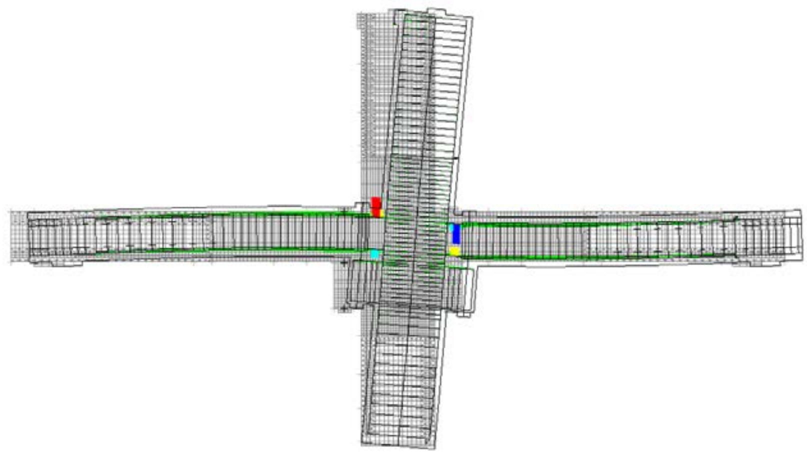


Figure 15 b) – Model B: stress in x-direction for load of 600 kN that it was applied at the top of the column.

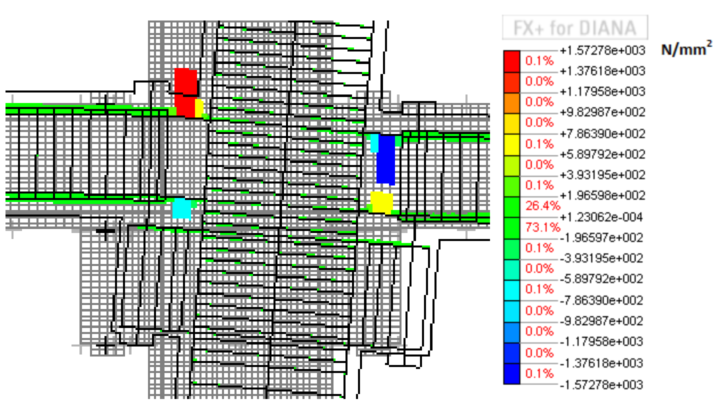


Figure 15 c) – Model B: zoomed view of stress in x-direction for a load of 600 kN applied at the top of the column.

Of course, besides the initial stiffness assessment, the results of linear analysis are not realistic. So full non-linear analyses are developed with the previous recalled hypothesis. Figures16 shows the force-displacement diagram for some of the cases studied and summarized in Table 2.

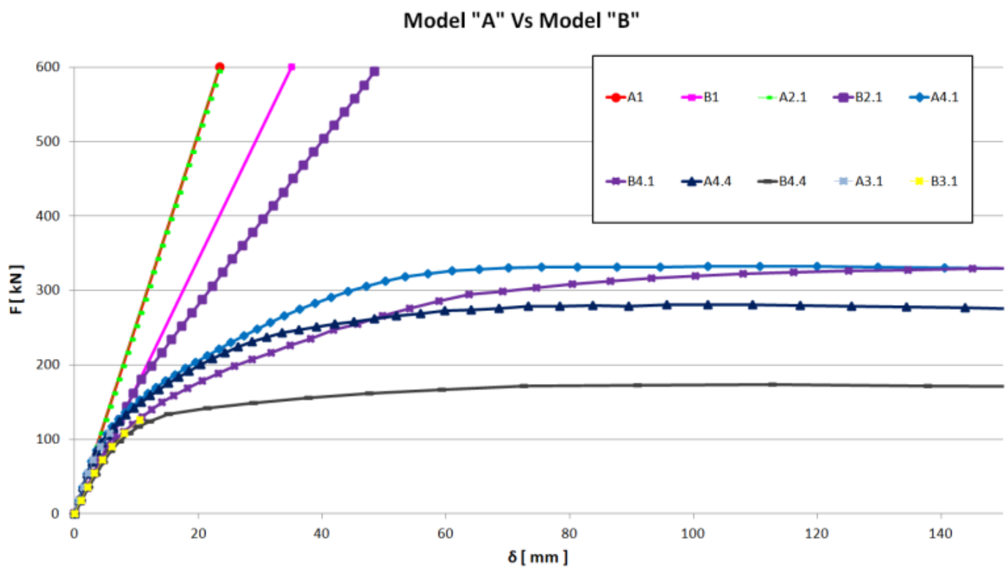


Figure 16 – Comparison among different force-displacement response of MODEL A and MODEL B (see also Table 2).

After this initial exploratory phase, the finally selected models for this study were “A4.4” and “B4.4” as they are the model whose behavior is more realistic.

The single force step is 18 kN for both the models. Beside global aspects as the overall diagram force-displacement response as in Figure 17, it is interesting to examine local aspects.

The crack-strain results at the integration points (first crack at integration point) are named E_{knn} in DIANA. Different load steps in order to show the cracking sequence are presented:

- MODEL A:
  - Step 7 – F=105.41 kN, when the behavior of structure is still linear-elastic;
  - Step 40 - F=280.9 kN, after reaching the maximum loading force;
- MODEL B:
  - Step 7 – F=107.6 kN, the behavior of structure is still linear-elastic;
  - Step 18 – F=173.1 kN, after reaching the maximum loading force.

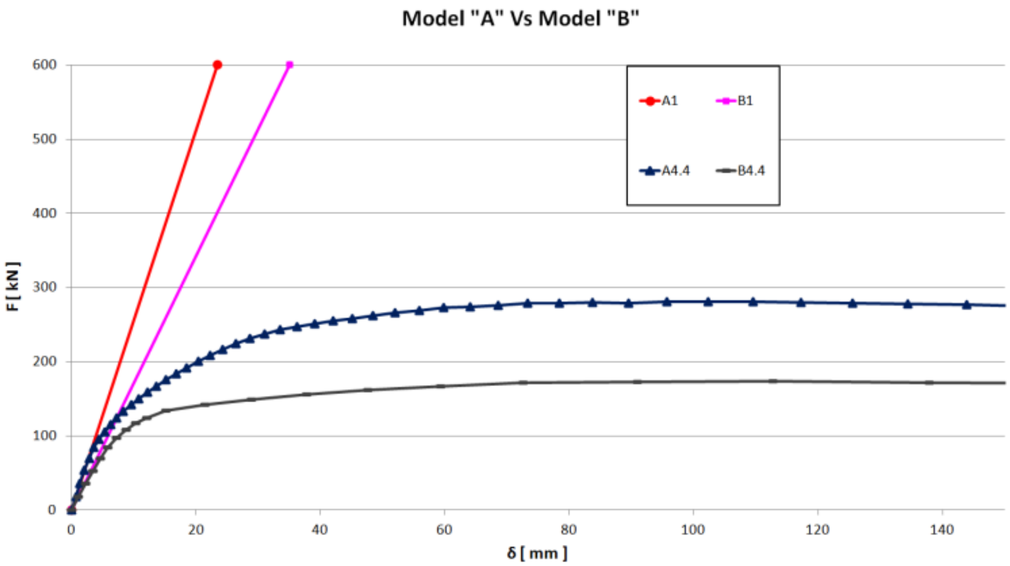
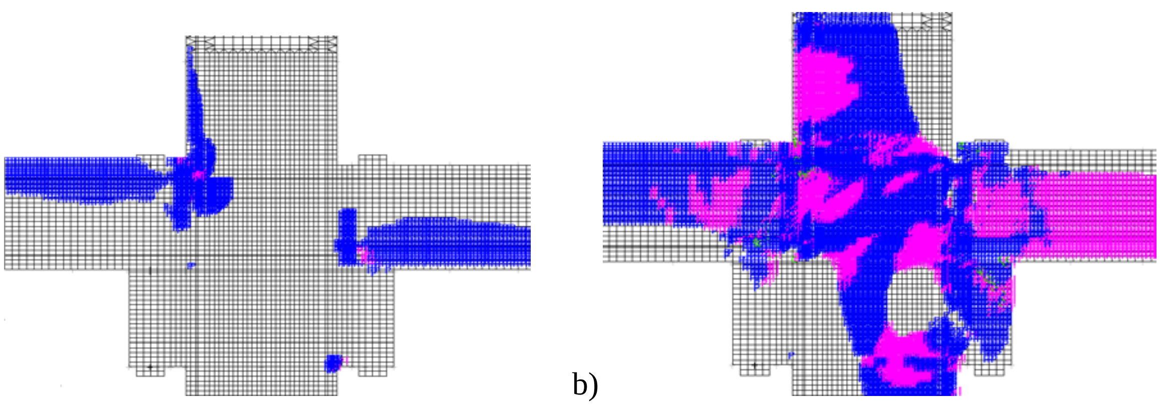
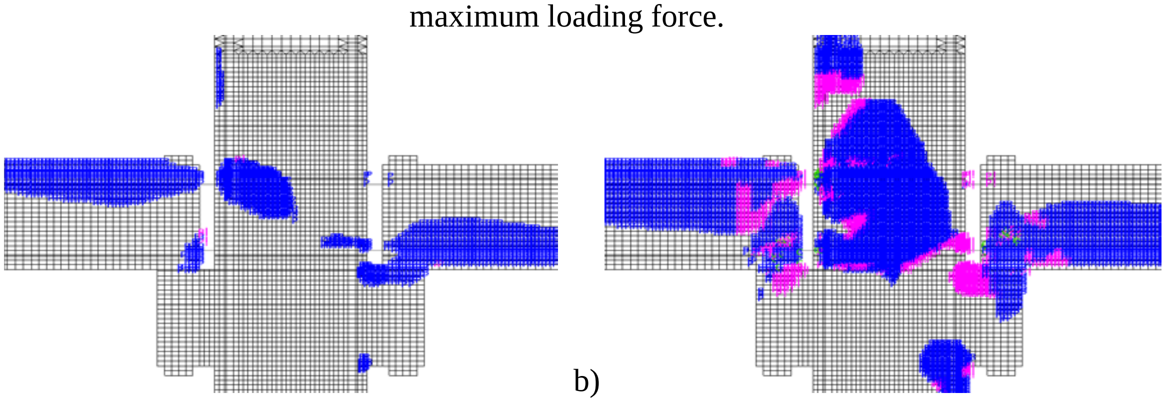


Figure 17 – Comparison between Model A and Model B.



a) b)

Figure 18 - MODEL A - CRACK STATUS: a) Step 7; b) Step 40, after reaching the maximum loading force.



a) b)

Figure 19 – MODEL B - CRACK STATUS: a) Step 7; b) Step 18, after reaching the maximum loading force.

Finally, also the correct representation of steel behavior must be checked: To this end, Figures 20 shows how the stress is developed in the steel parts of the models, following the prescribed law.

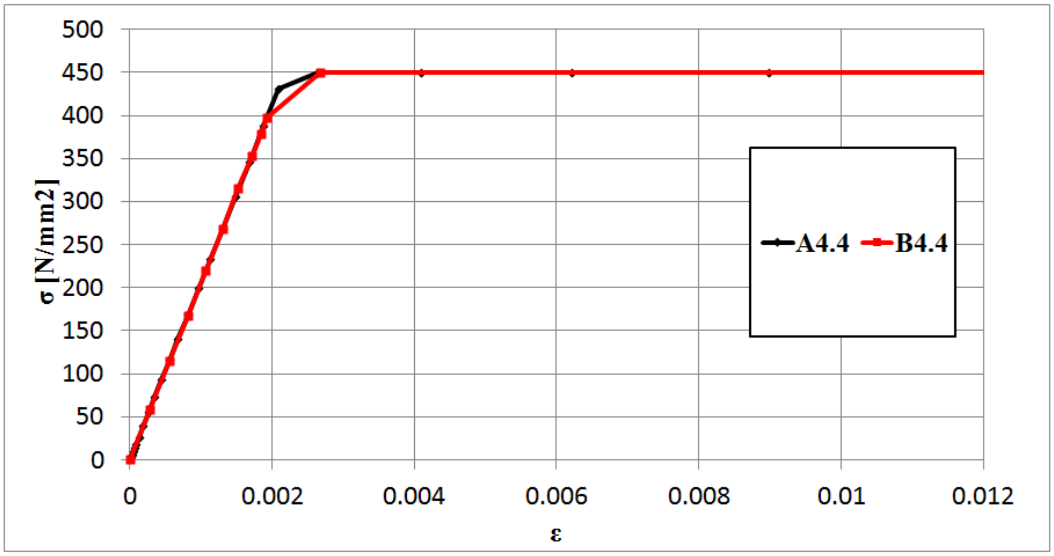


Figure 20 - Relationship between stress and strain for Model A and Model B of beam-column ductile connection.

THREE DIMENSIONAL MODELLING

For the three-dimensional modeling the steps that should be performed are the same of 2D Model. The creation of geometry is made by entering the coordinates from external files (.txt) to create points and then connecting the dots to create poly-lines and so DIANA® creates surfaces directly. Then with the command "EXTRUDE", the surfaces became solids.

Concrete, mortar, rubber and steel plates where any constraints and loads are applied, were modeled by a four-node, three-side iso-parametric solid pyramid elements whereas steel longitudinal reinforcements were modeled by two-node straight truss elements and the stirrups were modeled by two-node, two-dimensional class-II beam element.

For solid elements, the only physical property that is needed is the material. For the reinforcing steel the physical input is the cross-sectional area and for the stirrups the physical input is the diameter of the section.

The mesh scheme is shown in Figures 21: it consists in 158634 solid elements, 9106 bar elements, 31639 nodes for a total of around 142941 degree of freedom.
Figures 22-23 show details for Model A and Model B respectively, focusing on the concrete parts of the specimen. Details of the steel reinforcing layout are instead shown in Figg.24-25.

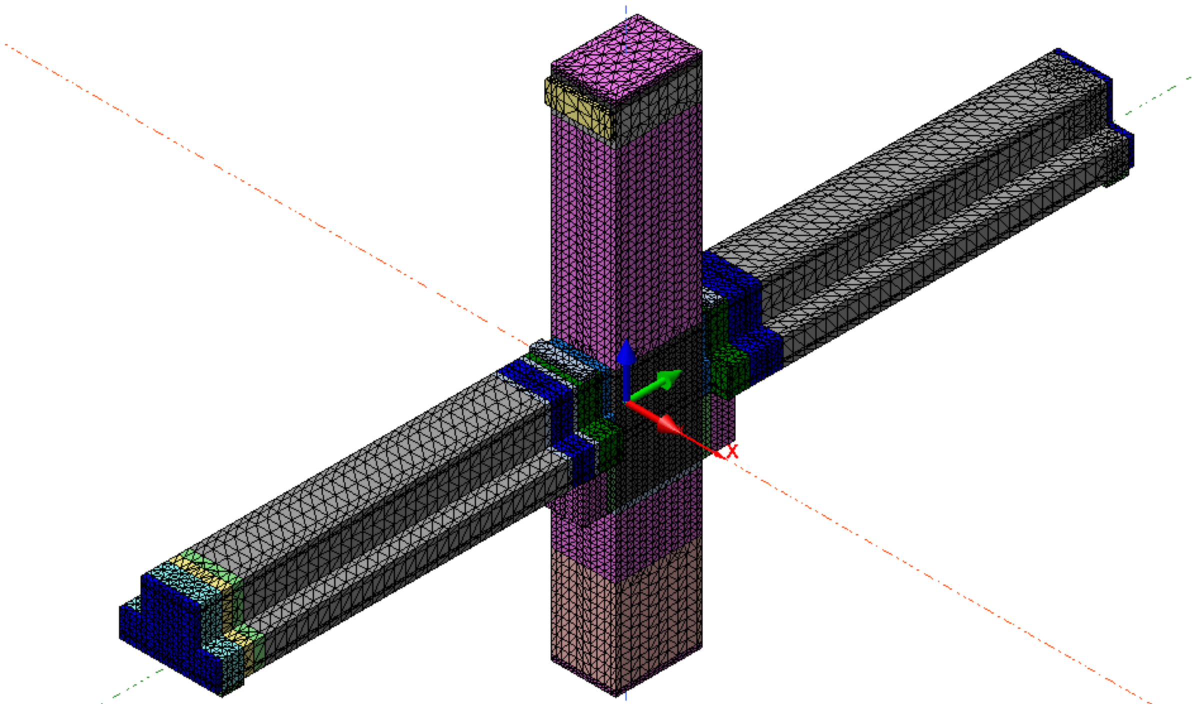


Figure 21 – 3D discretization for Model A.

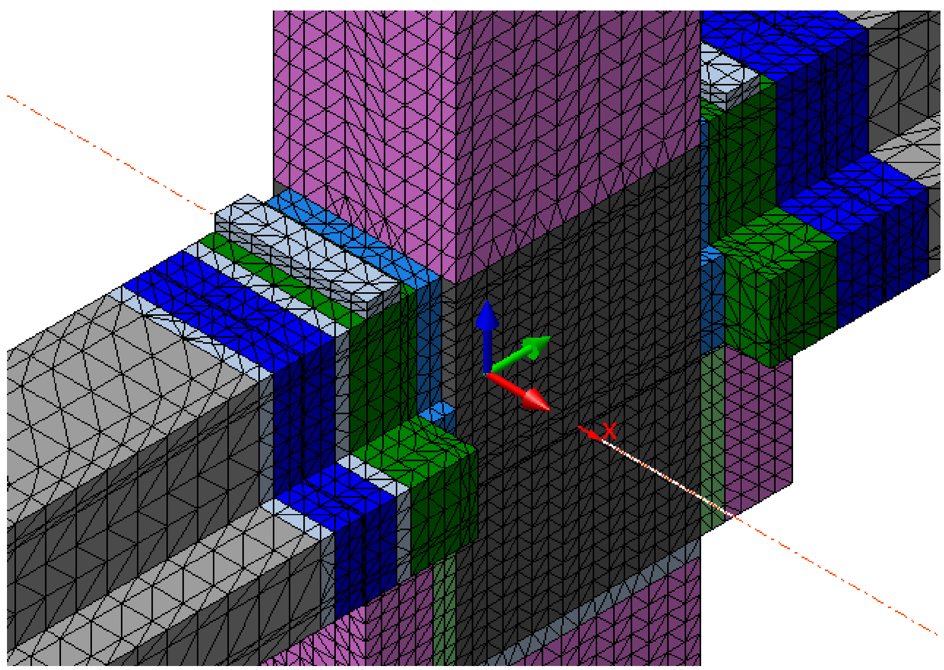


Figure 22 - 3D Model A: zoom of the mesh in the beam-column joint.

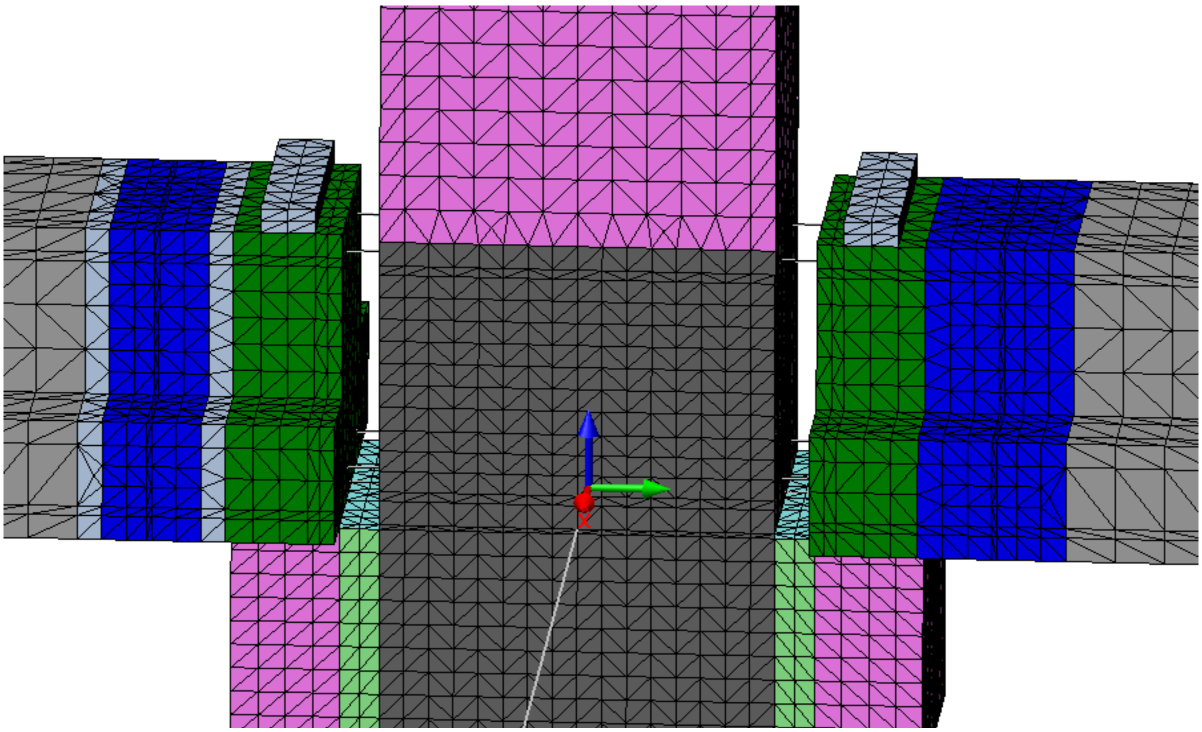


Figure 23 – 3D Model B: Zoom of the mesh in the beam-column joint.

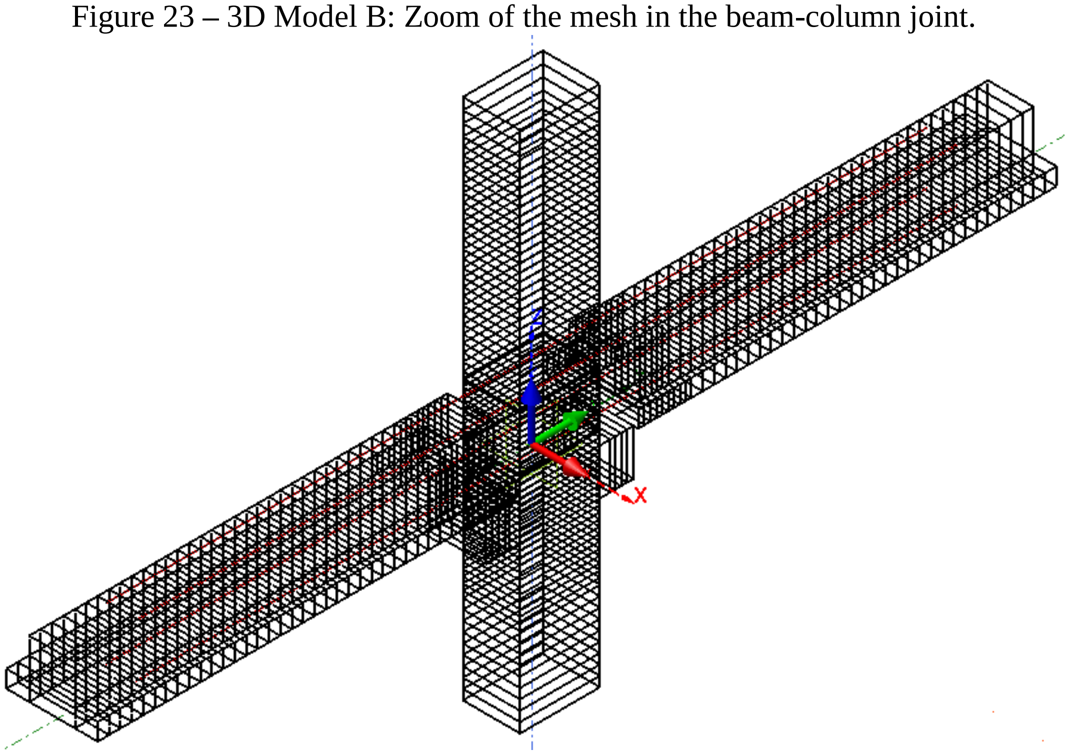


Figure 24 – Overview of the reinforcing steel layout of 3D modeling.

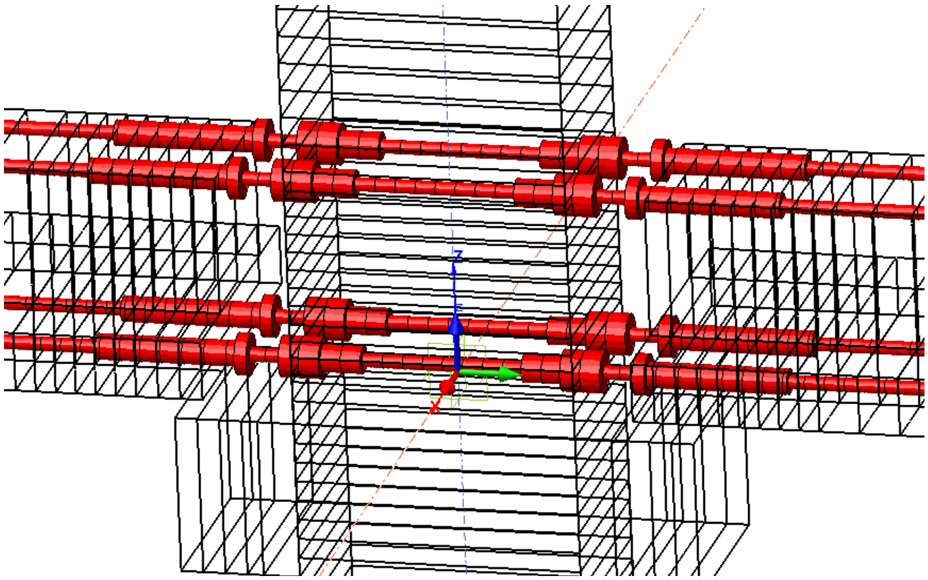


Figure 25 –Reinforcing steel of 3D modeling: zoom at the section of innovative solution for ductile connection.

BOUNDARY CONDITIONS AND LOAD

The boundary conditions and loads are the same of the two-dimensional model. Of course, suitable out of plane constraints are considered. A first preliminary linear analysis was performed and Figures 26-29 show partial results of this runs.

NONLINEAR ANALYSIS

In the following the results of the nonlinear analysis of the so-called "A4.4" and "B4.4" models are shown, starting with global response as in Figure 30.

An interesting diagram is shown in Fig.31: where are represented all the curves obtained with DIANA superimposed with the curves obtained with an independent analysis developed by Code ASTER®. In the opinion of the authors, this is a valuable graph, because it underlines the similarity between the simulations conducted in two independent ways, with redundancy of software and people.

Finally, in Figures 32 and 33 shows the crack-strain results at the integration points. Different load steps (Steps 1, 5, 15, 20) are presented in order to show the cracking sequence. Details for the stress level on the reinforcing bars are shown in Figures 34 and 35, from where it appears that the bars are fully plasticized: this development is of course important for the ductility requirements.

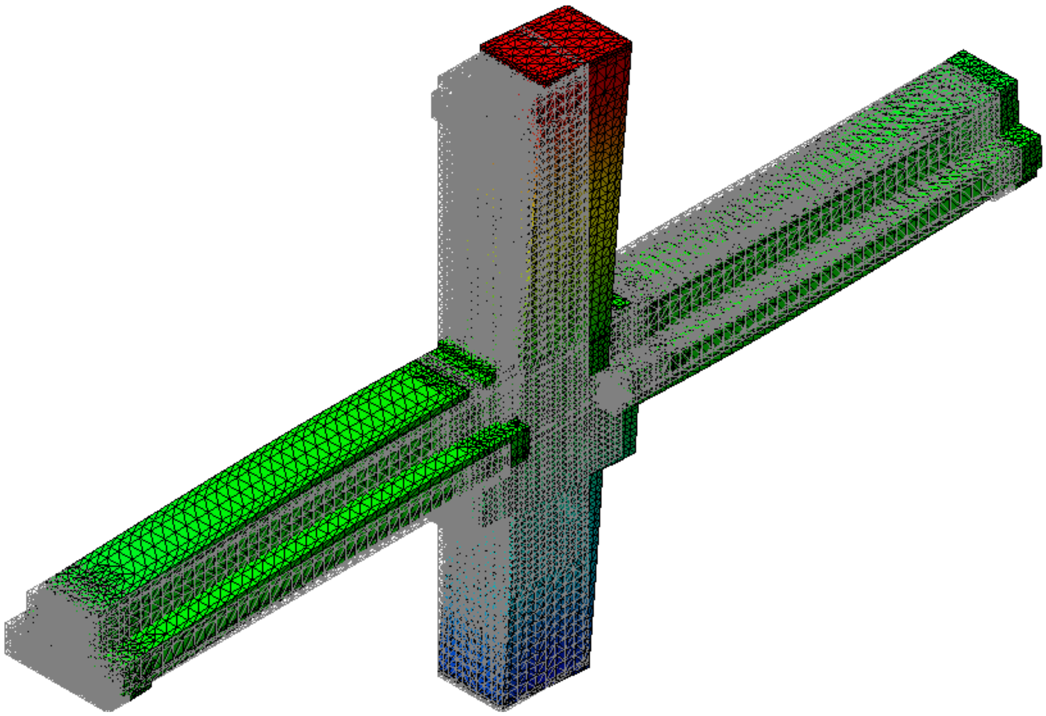


Figure 26 – Model A – linear analysis: top displacement of 19.2 mm.

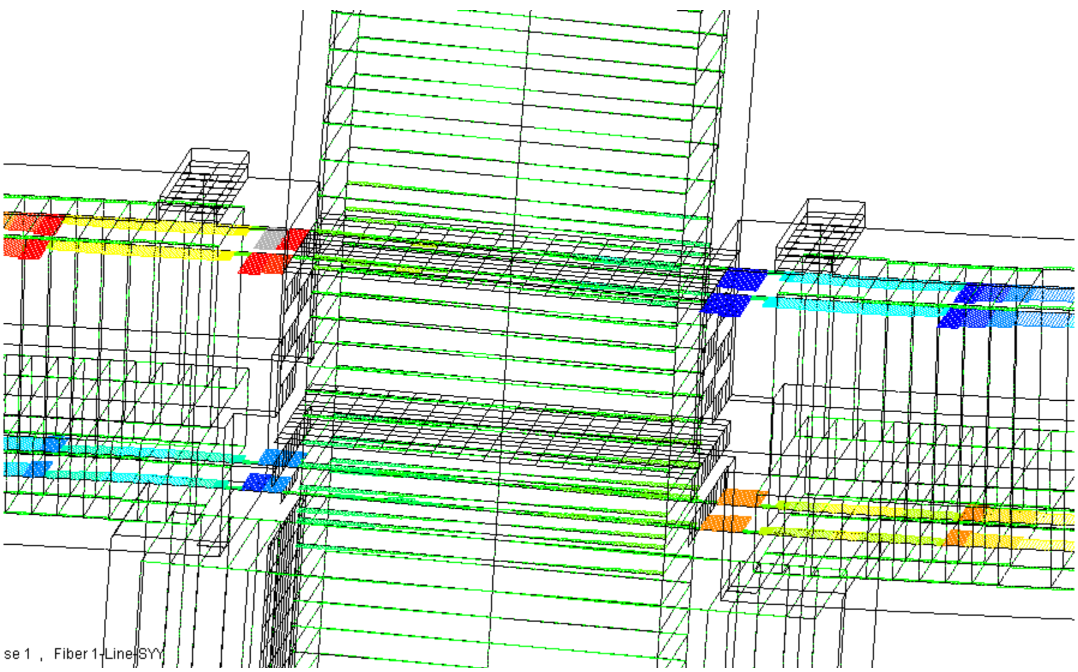


Figure 27 – Model A – linear analysis: zoomed view of stress in x-direction for applied load of 600 kN (max 184 N/mmq).

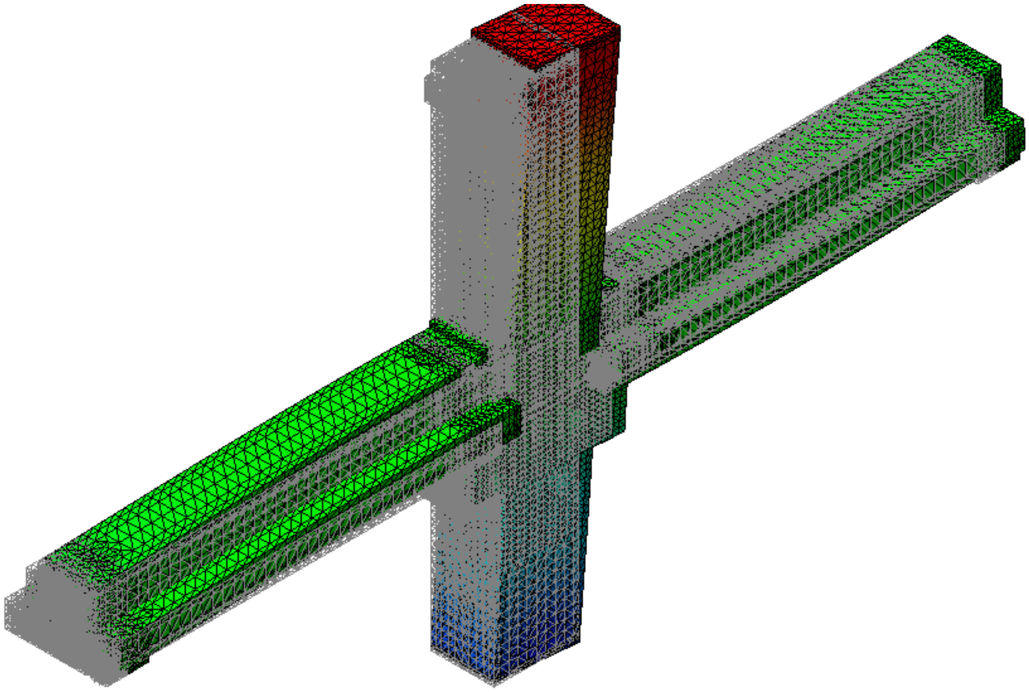


Figure 28 – Model B – linear analysis: top displacement 26.1 mm.

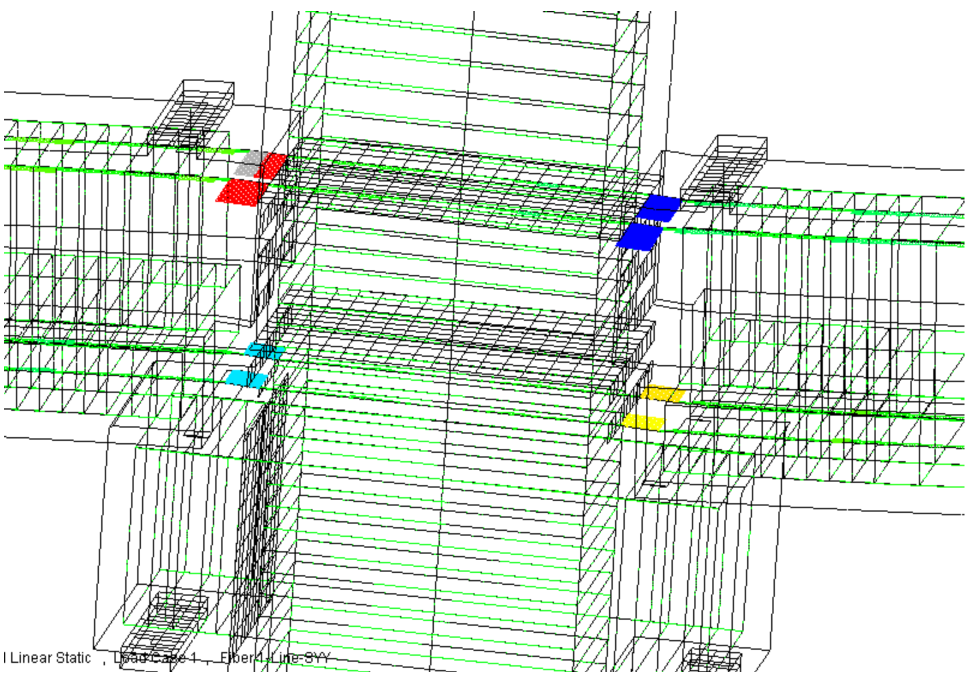


Figure 29 – Model B – linear analysis: zoomed view of stress in x-direction for applied load of 600 kN (max. 1028 N/mmq).

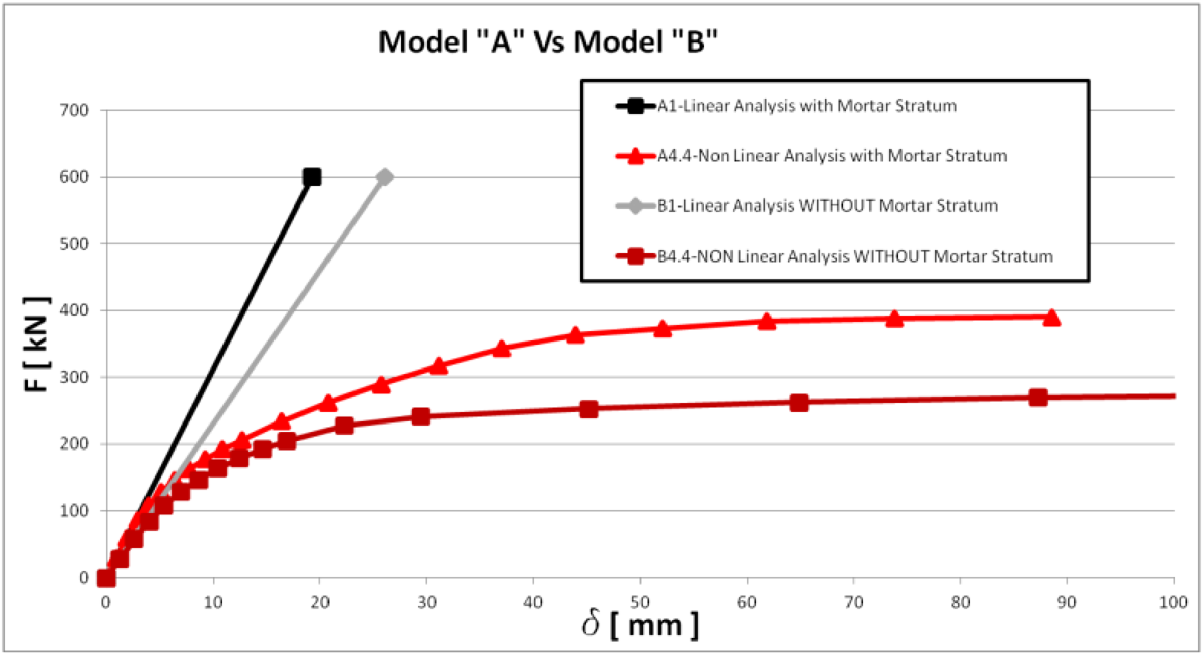


Figure 30 – Model A vs. Model B force-displacement responses from linear and nonlinear analysis.

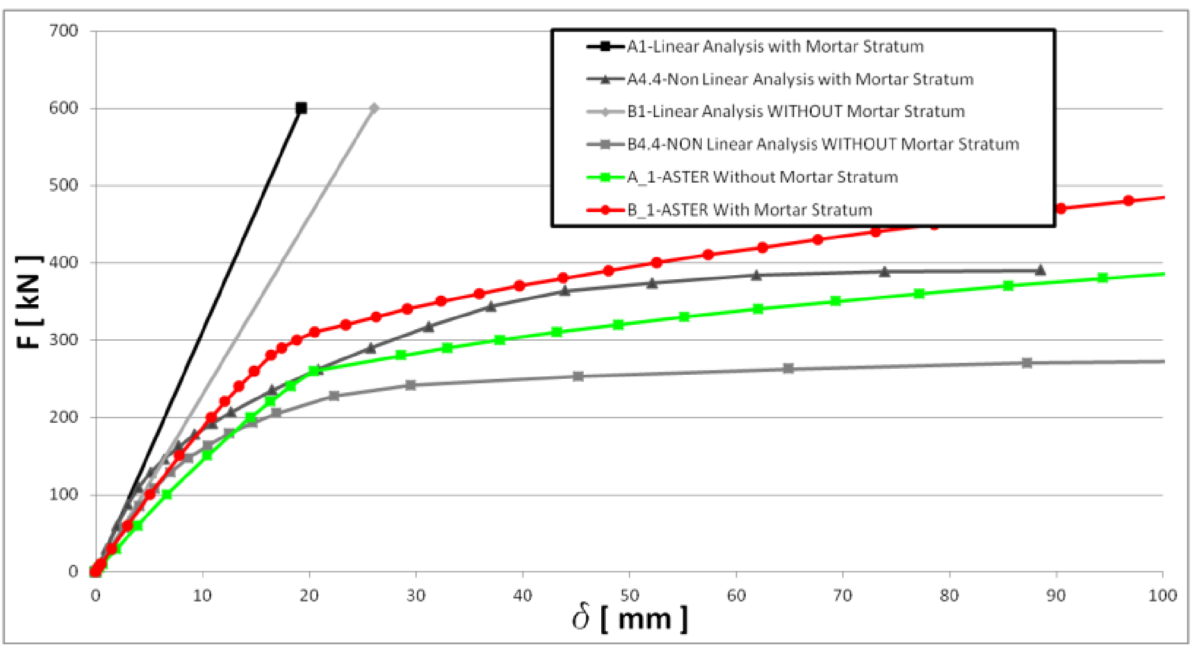


Figure 31 – Comparison between results obtained with DIANA® code and results obtained with ASTER® code.

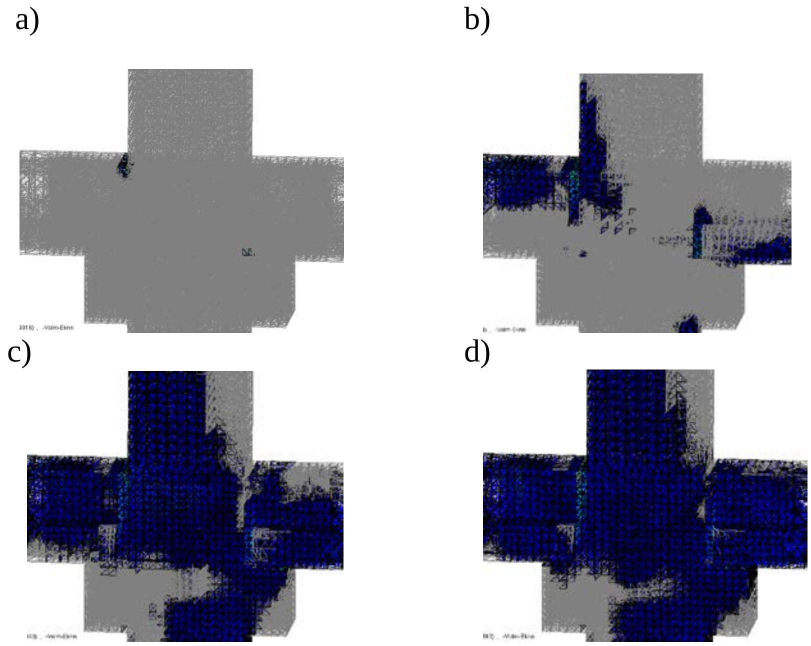


Figure 32 –Model A- Zoomed View of Crack Strain: a) Step 1; b) Step 5 c) Step 15; d) Step 20.

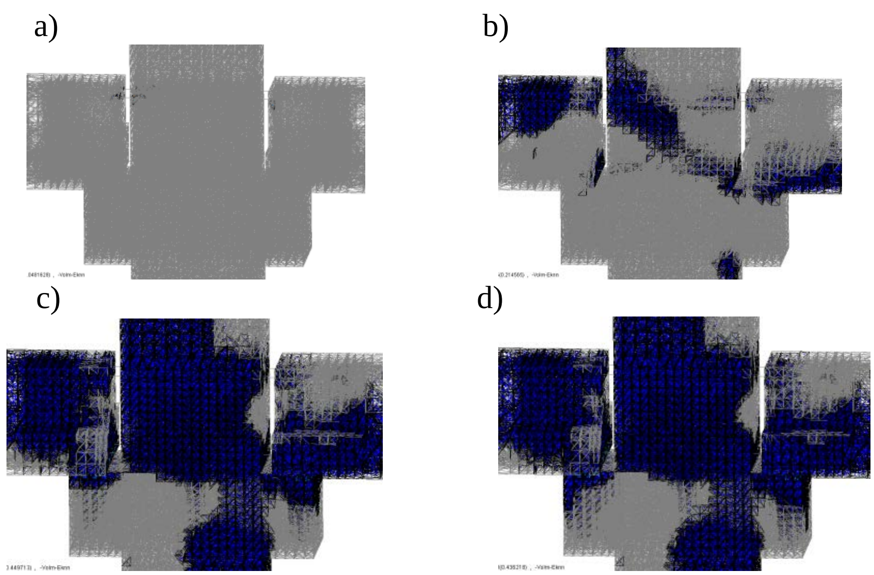


Figure 33 –Model B- Zoomed View of Crack Strain: a) Step 1; b) Step 5 c) Step 15; d) Step 20

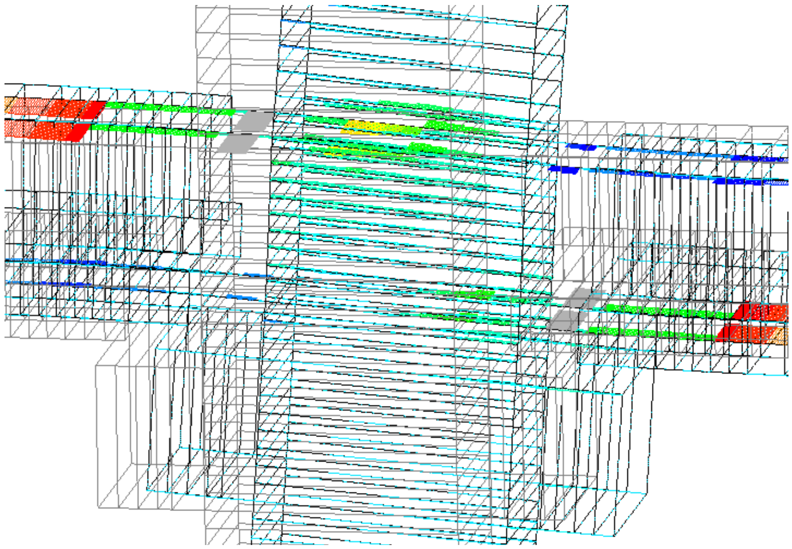


Figure 34 – Model A: zoomed view of steel stress (max 450 N/mmq, STEP 15).

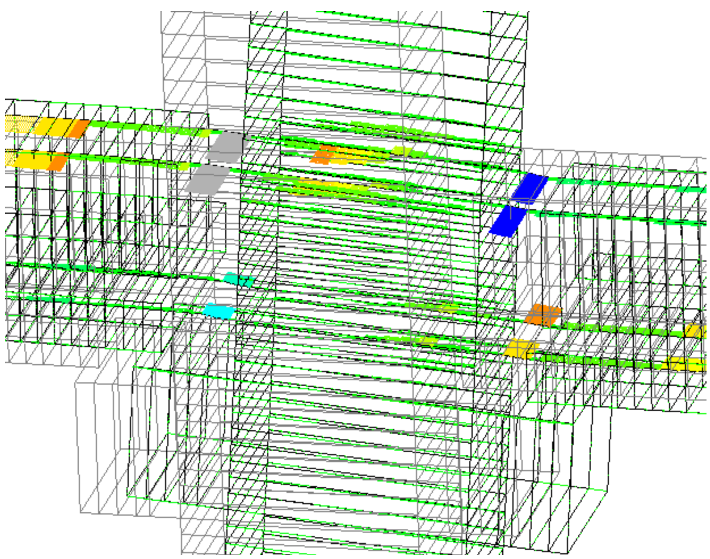


Figure 35 – Model B: zoomed view of steel stress (max 450 N/mmq, STEP 12).

CONCLUSIONS

In this paper the mechanical behavior of a quite innovative beam-column connection, usable for buildings and bridges, has been examined by a finite element analysis. To develop the numerical analysis it is used the DIANA® commercial software, with the explicit modeling of the nonlinear behavior of concrete and mortar using a total strain crack model. The reinforcing steel has been modeled by a classical bilinear plasticity model. A detailed

geometry of the system has been developed and meshed. The full load capacity of the coupling devices has been developed without brittle failures of the concrete and the mortar: therefore the connection system is well conceived, performing ductile behavior. Moreover the progress of the cracking of the concrete, well reproduced, appears regular.
An important result obtained is the similarity between the results obtained with two different finite element programs, the previously mentioned DIANA® and ASTER®. In this way, a complete sensitivity analysis for this specific kind of connection has been developed.
From the mechanical point of view, the role of the mortar stratum is weighted: the results show that the presence of stratum leads to a certain degree of increase both in the initial stiffness and in the final resistance. Another point of interest is the effect of the introduction of the connectors inside the mass of concrete: some worries were present about the possibility that this presence can develop brittle failure mechanism. This was not the case.
In particular, the overall response curves appear smooth and regular and in the coupling devices the plastic strains are developed, leading to an effective ductile connection system [8, 9].

ACKNOWLEDGEMENTS
Arch. Sergio Zambelli and Dr. Claudio Pagani of BS Italia / Styl-Comp Group, Zanica (BG), Italy are acknowledged for valuable discussions and suggestions.

REFERENCES

1. PCI Connections Manual for precast and prestressed concrete constructions, First Edition 2008.
2. CEB-FIB 2003. State-of-art report: Seismic Design of Precast Concrete Building Structures, International Federation for Structural Concrete (fib), bulletin 27, 2003, 254 pp. Lausanne, Switzerland,
3. TNO-DIANA - http://tnodiana.com/midas-FX-for-DIANA
4. Code ASTER - http://www.code-aster.org
5. Vecchio F. J., Collins M. P. 1986. The Modified Compression-Field Theory for Reinforced Concrete Elements Subjected to Shear, ACI Journal, Proceedings V. 83, No. 2, Mar.-Apr. 1986, USA: pp. 219-231.
6. Vecchio F. J., Collins M. P. 1993. *Compression Response of Cracked Reinforced Concrete*, Journal of Structural Engineering, ASCE, 119.
7. Feenstra, P. H. (1993): Computational Aspects of Biaxial Stress in Plain and Reinforced Concrete, PhD thesis, Delft University of Technology, Holland.
8. ACI Committee 318, "Building Code Requirements for Reinforced Concrete (ACI 318-08)," American Concrete Institute, Detroit, Michigan, 2008.
9. ACI-ASCE Committee 352, "Recommendations for Design of Beam-Column Joints in Monolithic Reinforced Concrete Structures," Journal of the American Concrete Institute, Vol. 82, No. 3, May-June, 1985, pp. 266-283.