EVOLUTION OF THE DESIGN OF A CABLE-STAYED BRACKET

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ABSTRACT

In these last years, the design of precast structural elements has remarkably changed showing very sophisticated approaches to allow satisfying all the compound requirements of modern constructions. Specific problems are connected with architectural and esthetically driven requirements which lead to a strong search for compact and minimal configurations of structural parts like brackets. At the same time, also the structural response must be optimized with regards to functional and ultimate responses but also with respect to structural robustness aspects. Furthermore, the possibility to include also dissipative devices is considered.

In the present work, the evolution of the design of a bracket component, supported by a cable-stayed system, is presented. This apparently simple element conceals a rather complex structural geometry, developed to be suitable both for strength requirements and constructability. The so devised solution can assure:

- Manufacturing of precast elements without exterior parts;
- Minimal size of the bracket and completely hidden insertion in the supported beams;
- Compliance with different standards.

The evolution of the leading concepts and of the geometry of this element is explained together with the numerical analysis obtained both by synthetic models, like strut & tie, and by full non linear finite element models.

Keywords: Innovative Precast Structures, Connections, Optimization, Structural Robustness

INTRODUCTION

It is well known that crucial aspects of precast concrete structures are the connection regions. Here one finds:

1) Presence of high stress levels;
2) Diffusive field of stress, leading to the so-called D-regions;
3) Geometrical complexity, related to the position and interference of different structural parts converging there;
4) Requirements of minimum space usage, essentially due to architectural appearance;
5) Necessity to guarantee a substantial good structural behavior, i.e. strength, ductility, and robustness of the connections;
6) Demand from a constructability point of view.

It is not exaggerate to say that the overall goodness of a precast structure design is mainly based on the conception and practicality of the connections between the different structural parts and elements. In this paper, the evolution of the design of a cable stayed bracket system for the support of precast beam is considered starting with the leading concepts. The geometry of this element is explained together with the numerical analysis obtained both by synthetic models, like strut & tie, and by full non linear finite element models.

BASIS OF DESIGN AND PERFORMANCE CRITERIA

Before any quantitative evaluation, it is important to fix the design basis for such a kind of innovative connection.
These design criteria are ordered as in the follows:

a) <u>simplicity</u>:
   the structural configuration of the connection must be made by very regular and flat parts, by which
   - the stress state has the most possible uniformity;
   - there are no stress concentrations;
   - the load transfer is obtained by the most straight path;
   - it is possible to develop a complete integration between steel parts and concrete mass, with an accurate structural anchorage.
b) <u>dependability</u>:
   the structural configuration must have
   - suitable functional performance characteristics (Serviceability Limit States, SLS),
   - appropriate strength capacity (Ultimate Limit States, ULS),
   - capacity to support accidental situations, without showing disproportionate consequences when triggered by limited damage (Structural Robustness).

To assure these criteria, one must assess the following points:

1. <u>Ultimate Limit States (ULS):</u>
   - the strength aptitude is verified by the partial safety coefficient format of limit states, assuring the achievement of the equilibrium condition between load demand and strength capacity;

- in the previous recalled equilibrium situations, it is allowable to have some yielding regions inside the steel parts and some crushing and cracking in limited space in the volume of the surrounding concrete;
- the strength capacity must be checked by structural analysis that takes fully into account the material nonlinearity, starting from the undeformed/unloaded situation up to the collapse situation;
- the structural modeling must be at the end capable to represent the geometry complexity, specifically the entity of the yielding steel parts and the crushing/cracking zones of the concrete;
- the overall judgment of the validity of the connection, must be also based on the extension and in the location of these regions and zones;

2. Serviceability Limit States (SLS):
   - the structural response must be essentially linear until a load level equals to the design ultimate limit load divided by 1.5;
   - the steel parts don't have to show essential yielding and concrete must be in a limited stress state;
   - the connection displacements must be restricted to assure functional requirements and to avoid any disengagement between the connected structural elements;
3. Structural Robustness:
   - the inserted connection must develop collapse after the structural element is placed in;
   - the connection must be able to support, also with relevant yielding and concrete damage, the rupture of one of the two steel stay that are present; in this way, each stay and the connection must be able to support, also with great damage, a load level corresponding to two times the service load level.

DESCRIPTION OF THE SUPPORT

The structural decomposition of the innovative cable-stayed connection under study is shown in Fig.1. Essentially, one has the external bracket that in this first version is simply composed by a horizontal plate and four vertical ribs connecting a horizontal articulated joint, and a more complex internal part. There, first of all there is one couple of ties, one of each side of the column, that support the external bracket being connected to the horizontal articulated joint. The ties are anchored in a plate fixed on a sort of frame, made by four vertical plates, acting as global ribs, connected by two bottom plates.

Fig.2 shows several aspects of the real form of the cable-stayed innovative connection under study. On the two pictures on the top, one finds the final appearance of the connection inserted in concrete columns, during the construction phase of a precast building. One immediately recognizes the exterior compactness of the connections, while the complexity of the connection is concealed inside the column. In fact, the two pictures on the bottom show the inner part of the connection inside the concrete column reinforcement cage. Finally, in the two figures on the top, one can also perceive the horizontal articulated joint and the end of the ties having spherical appearances.

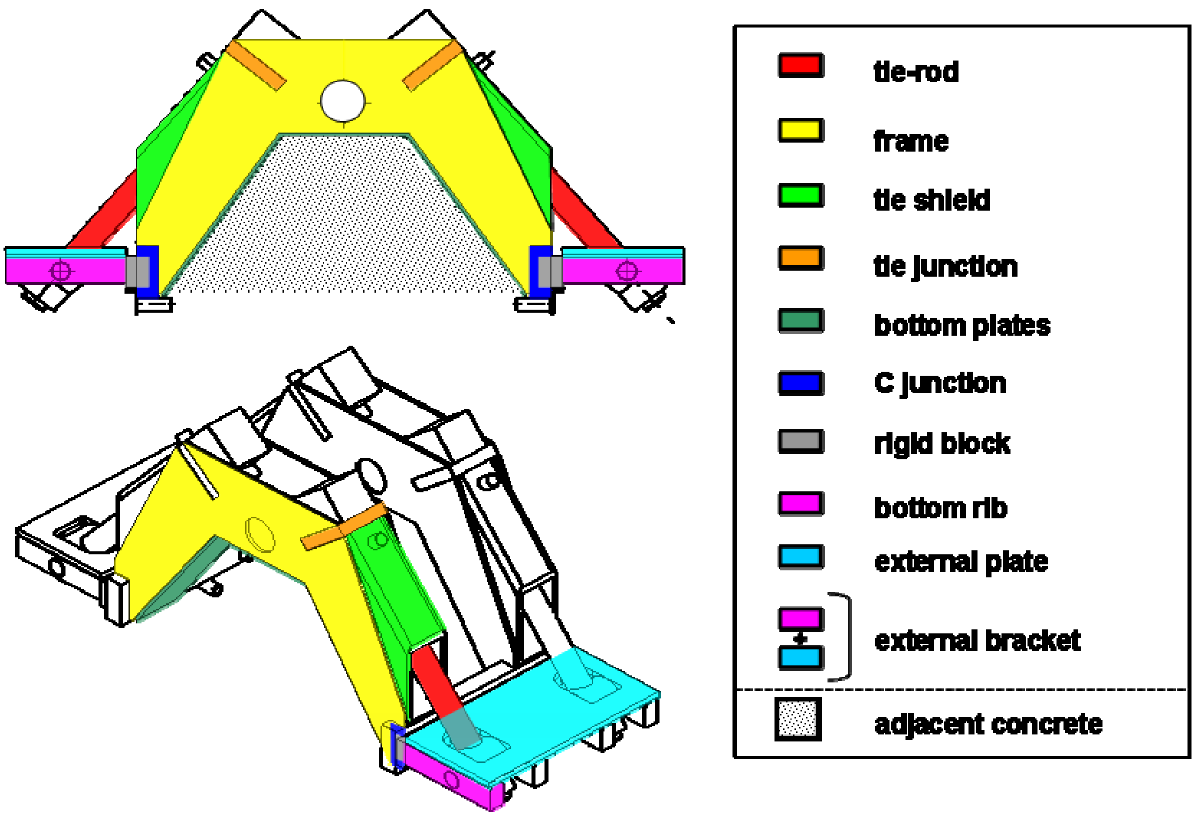


Fig.1: Structural decomposition of the cable-stayed innovative connection under study.

Fig.3 shows the two main loading configurations: while the first one is symmetric, representing the case where the column is loaded from both side, the second one is more interesting, from the mechanical point of view: in fact, also if associated with a minor load, it can represent a limiting situation due to the larger moment and the unbalanced action.
By the way, the considered vertical loads Vsd during this study were 600, 850, 1050, 1550 kN, and the connection configuration was defined in a parametric way to define a full family of device for different load necessity.
Fig.4 shows the main assumption adopted in the first part of the design study, i.e. symmetry about the mid plane: this hypothesis will be rejected when one passes to the full three dimensional analyses as explained below.
The materials for the connection were initially chosen as usual laminated steel for all the plates and high strength steel for stays. The only unusual material is the one adopted for the articulated joint, which is nickel-chromo based special steel.
In the following, the modeling activity and the analysis that lead the evolution of the design of this kind of innovative cable-stayed connection are synthetically recalled. It is relatively usual to follow this path when studying precast structures, but it is always difficult to communicate how much theoretical work is behind a so small structural part.
By the way, commercial finite element codes as *ANSYS*, *NeNASTRAN* and *STRAND* were appropriately adopted, while *ARGON ASHLAR VELLUN*, *ALIBRE* and *SOLIDWORKS* were used for the representation and the manipulation of the geometry.

Fig.2: Aspects of the cable-stayed innovative connection under study.

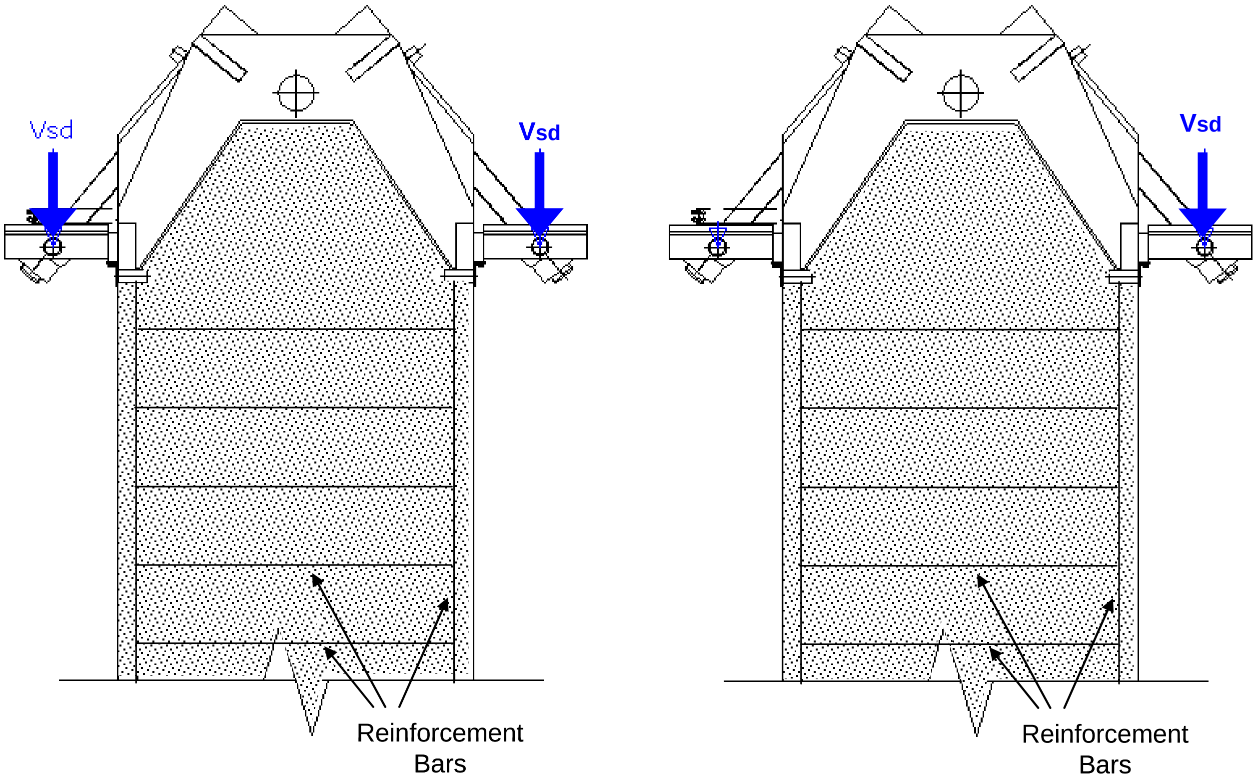


Fig.3: Basic symmetric / asymmetric load configurations.

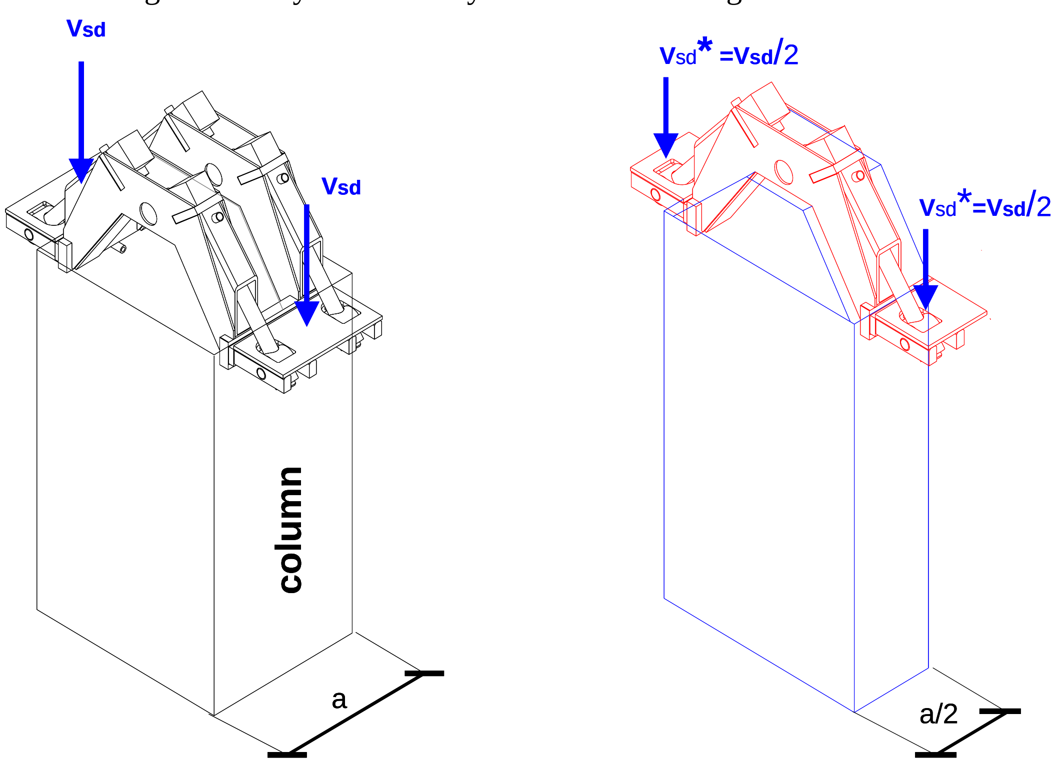


Fig.4: Symmetry considerations for the first analysis.

FIRST CONFIGURATION AND FIRST MODELING: STRUT & TIE AND MIXED REPRESENTATION OF THE CONNECTION

From Fig.1 to Fig.4 one has obtained the main idea about the connection under study. The modeling of this structural part must be developed in different stages, to methodically introduce the different aspects of the real object.
For thes reason, one starts with models that synthetically give the whole behavior (1) and then one face detailed models (2), also, very refined, to catch more specific point of view.
Specifically, Fig.5 shows the steps connected with the individuation of the load path inside the steel plates of the frame. The nodes so established form the basis for the discrete modeling by Strut & Tie. It is clear that more refined and realistic model will be considered, but from here one can develop an idea about the load transfer mechanism, the definition of the main parts of the connections, and establish the basis for the optimization process about device topology and material thickness.
Specifically, one develops:

I. Discrete models by Strut & Tie (S&T);
in these models, the steel parts, the longitudinal bars and the stirrups are represented by bars working both in tension and in compression, while concrete parts are lumped into bars with no tension behavior; furthermore:
- one model is a segment of concrete column sufficient to extinguish the diffusive effects connected with this D-region, i.e. until a B-region is reached, governed by the so-called Bernoulli stress regime;
- for the concrete, one has adopted a special link element with no tension behavior, and sectional areas obtained by energetic equivalence in the spirit of truss work formulation;

II. Mixed S&T – Finite Element models:
As for the concrete, for the steel parts one has adopted a discretization by finite element with formulation in plane stress.

Fig.6 shows the global arrangement of the full discrete models and of the mixed models. Also the end restraints at the base of the segment of column considered. Fig.7 shows only subsequent discrete models, to assess the validity of the results.
Fig.8 shows typical results obtained by S&T models: it is interesting to note the possibility to obtain rather expressive results for the stirrups and on the longitudinal bars, interesting for the anchorage of the connection into the concrete core, and for the stress on the concrete, considering also the no tension response.
Fig.9 shows some details of the mixed model: the main frame, as composed by steel plates, is modeled by finite element based on the plane stress assumption, while special elements represent the restraints of the stays. From this kind of model, one can obtain rather detailed response characteristics; in fact, for example:

- Fig.10 shows the load-stress and the load strain diagrams under symmetric loading case for the point in the middle of the frame as marked; these diagrams are obtained for different design load levels, and show on the whole a very good linear trend;

- on the contrary with the punctual information given previously, Fig.11 gives the whole load-displacement for the external point of the bracket, for the symmetric cases; here one finds a linear behavior for service load levels, while then one has the evidence of nonlinear behavior, as integral results of yielding in some part of the steel parts; on the whole, the behavior appears agreeable;
- similar considerations can be developed from Fig.12.

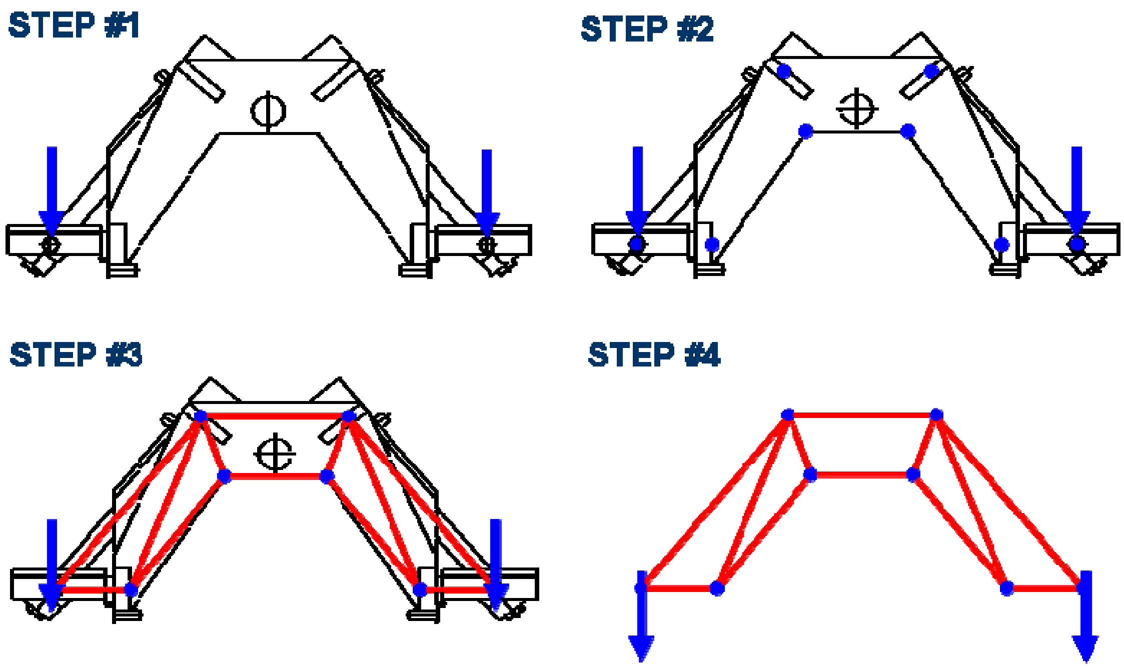


Fig.5: Main aspects of the load path for the cable-stayed innovative connection under study.

Conclusive appraisals can be obtained by Fig.13: here the stress field for the Von Mises Yielding Criteria considering the load *Vsd = 1050 kN* is represented. The frame plates have a *12 mm* thickness: at the top, one has the symmetric load case, while, at the bottom, one has the asymmetric load case. In the stress contour, gray area enlightens the regions where yield is reached. These regions appear limited and not connected, assuring also from this point the tolerability of the stress regime. By the way, this visual examination remains crucial in judging complex stress states, beyond numerical values.

Fig.14 permits to appreciate the evolution of the configuration of the cable-stayed bracket as consequences of the development of the analysis. It is interesting to observe the change in the skyline of the plates for the frame. Furthermore, one can perceive the presence of holes necessary to compose the frame essentially with mechanical composition starting from plane plates obtained by automatic cut laser.

It is clear that plane representation cannot grasp these aspects: in the next section, we will show some detail of the full three-dimensional analysis.

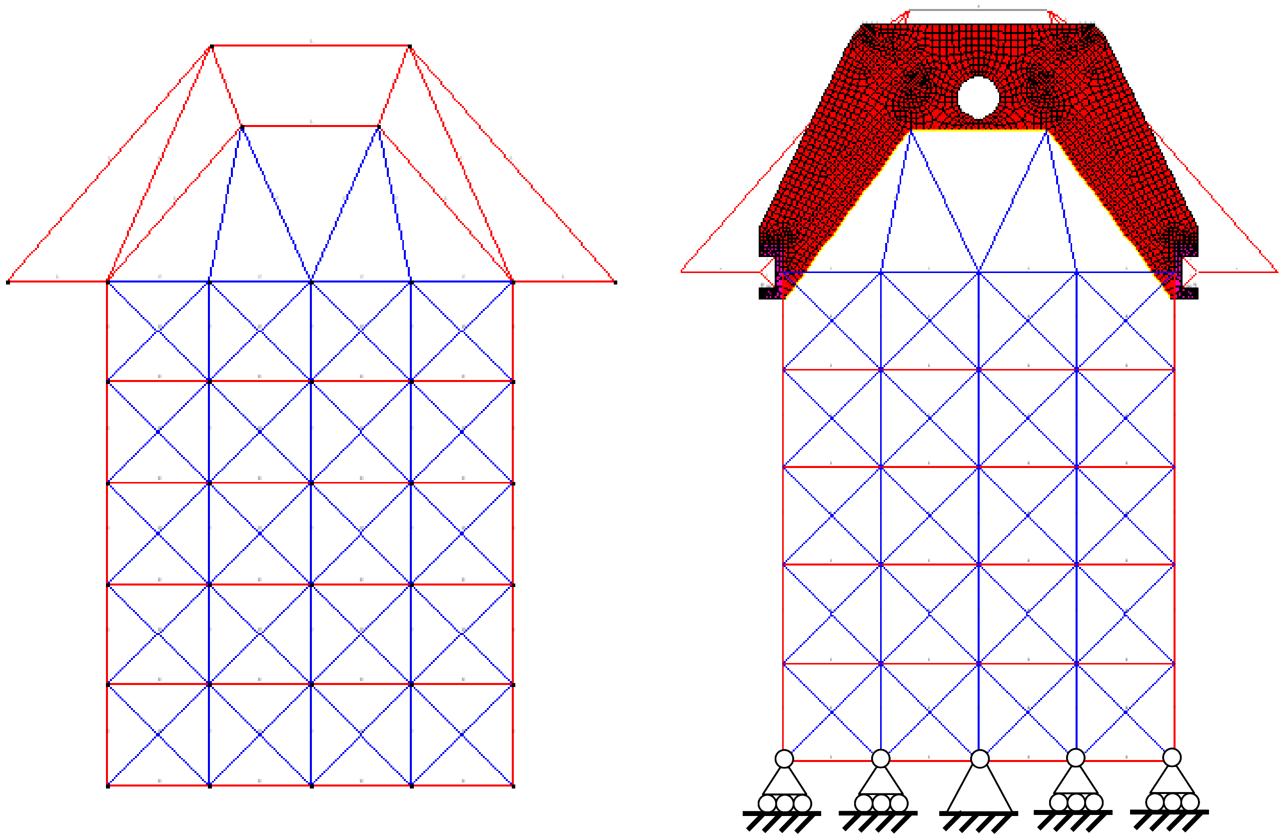
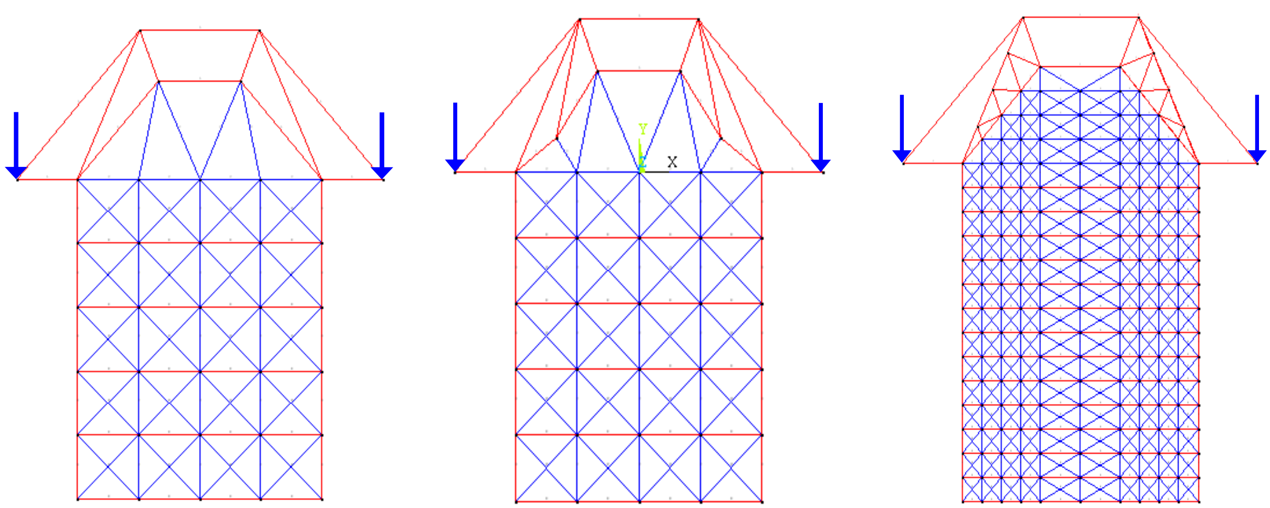


Fig.6: Full discrete (S&T) and mixed (FEM – S&T) modeling of the connection with base restraints.



Model #1	
Elements	135
Nodes	36

Model #2	
Elements	141
Nodes	38

Model #3	
Elements	867
Nodes	341

Fig.7: Aspect and characteristics of subsequent different S&T models.

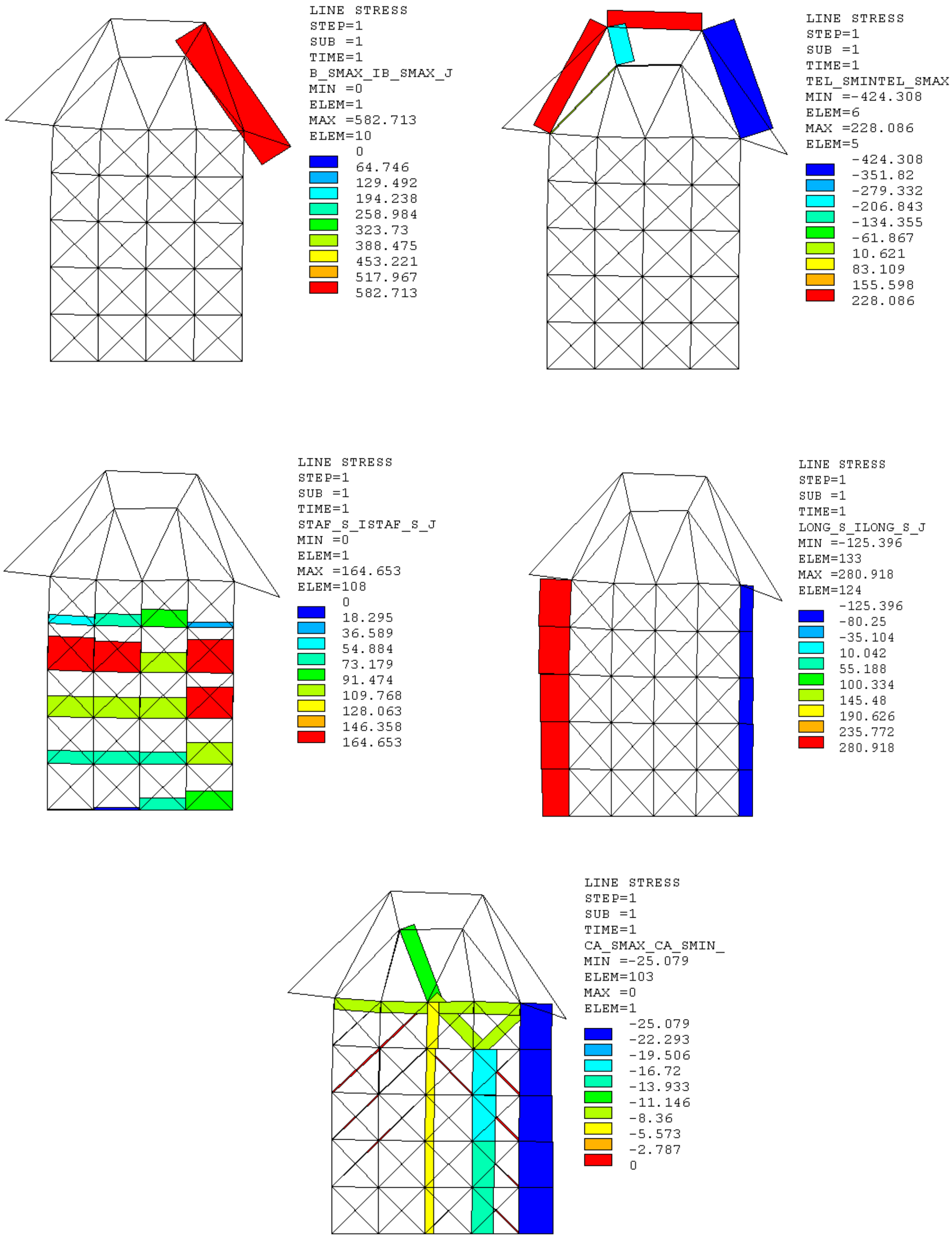
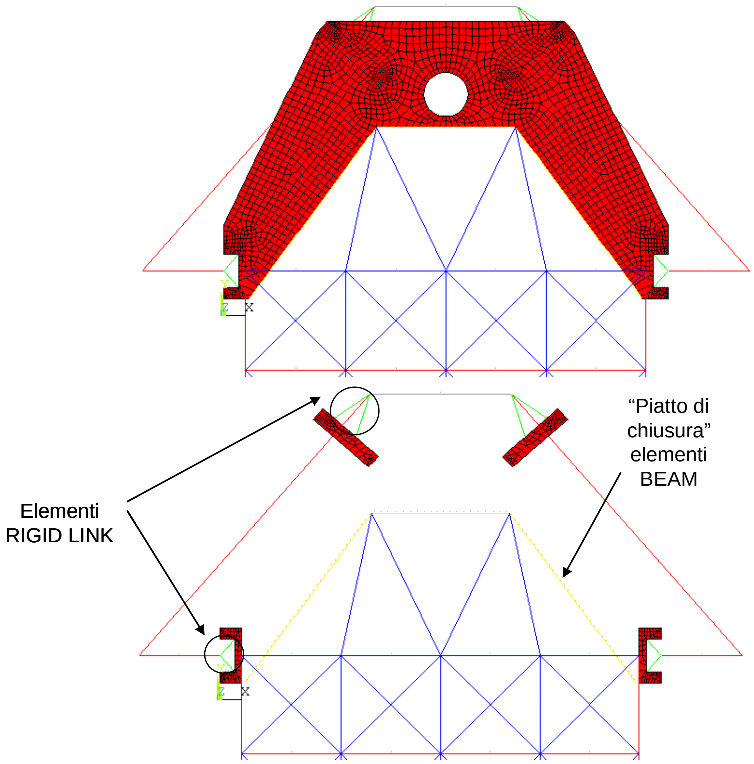


Fig.8: Typical results from S&T model: for the asymmetric load, on the top, axial actions on the bars representing the frame f the connection, in the middle stress on the stirrups and on the longitudinal bars, on the bottom, stress on the concrete core (please note the no tension response).



Mixed Model	
Finite Elements	1818
Bars	224
Nodes	5816

Fig.9: Mixed model: top, main frame, bottom, details for the restraints of the stays.

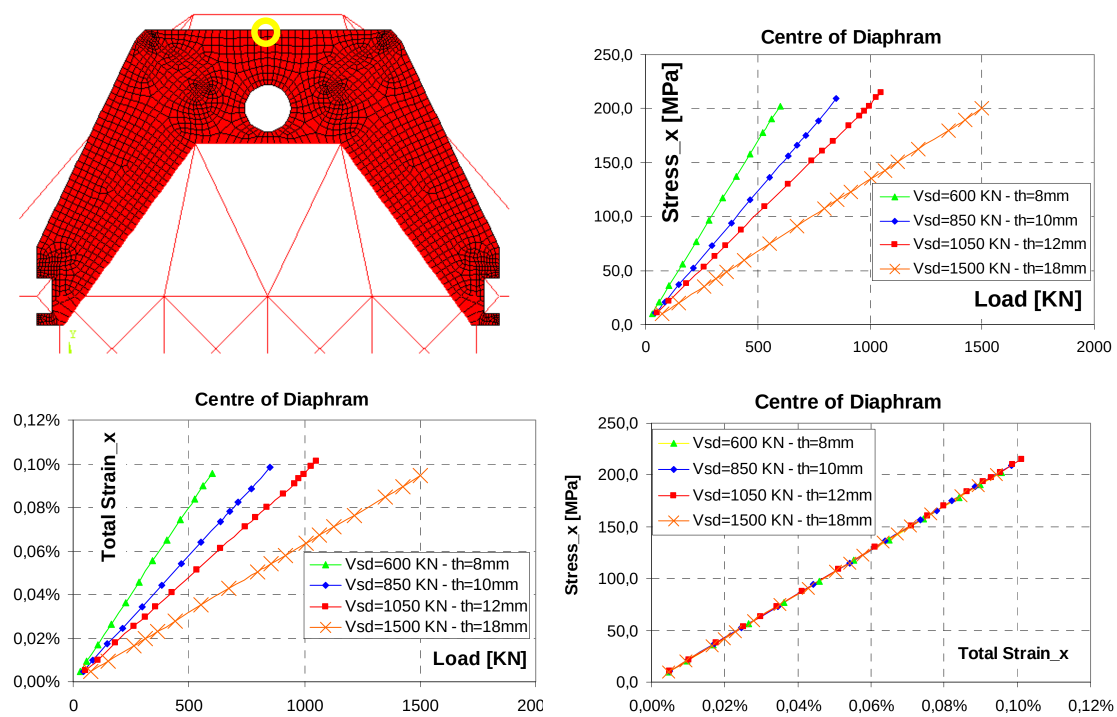


Fig.10: Load-stress and load strain diagrams under symmetric loading case (marked point).

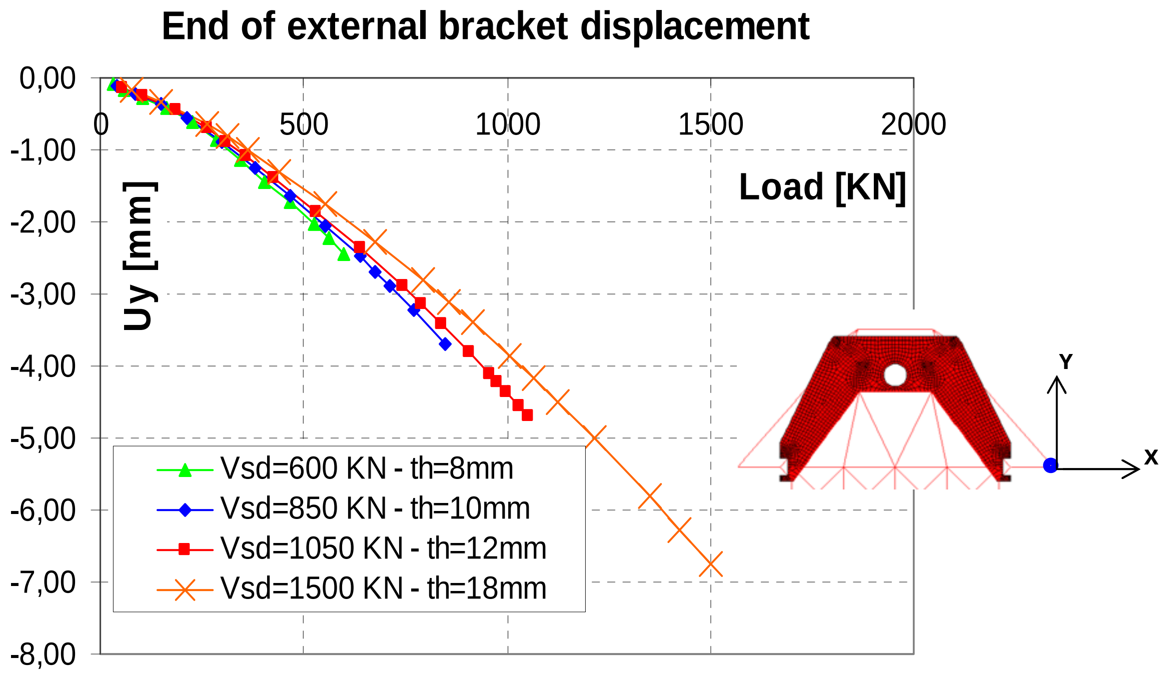


Fig.11: Load-displacement for the external point of the bracket, for the symmetric cases.

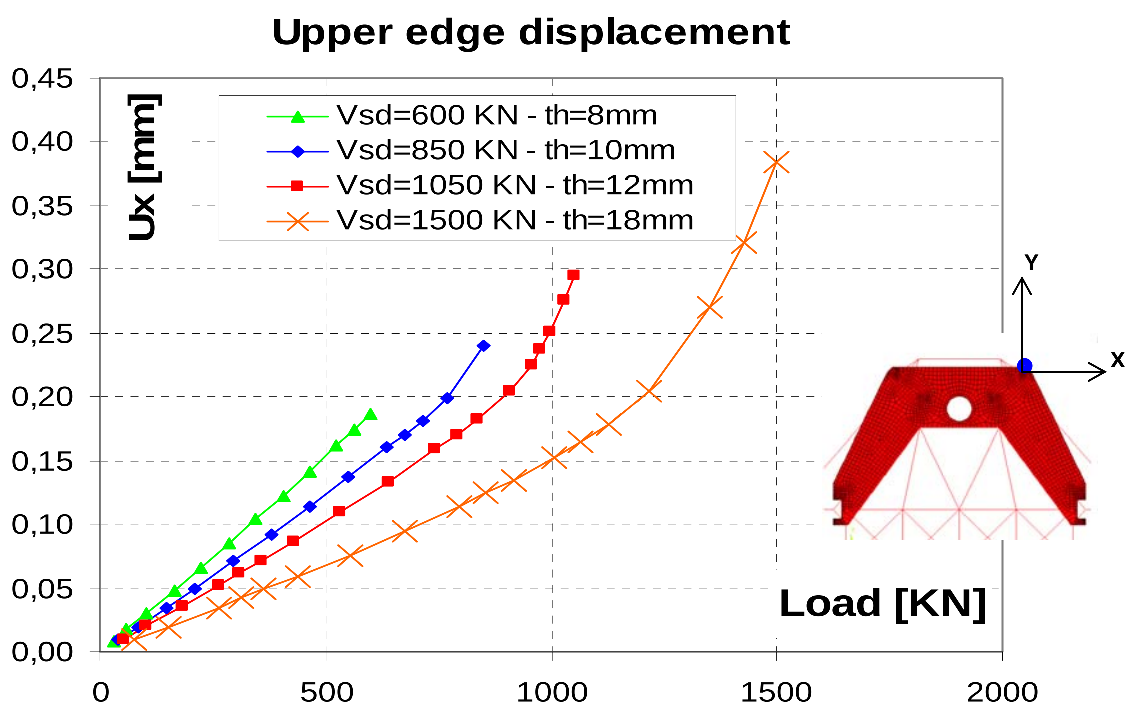


Fig.12: Load-displacement for the external point of the frame, for the symmetric cases.

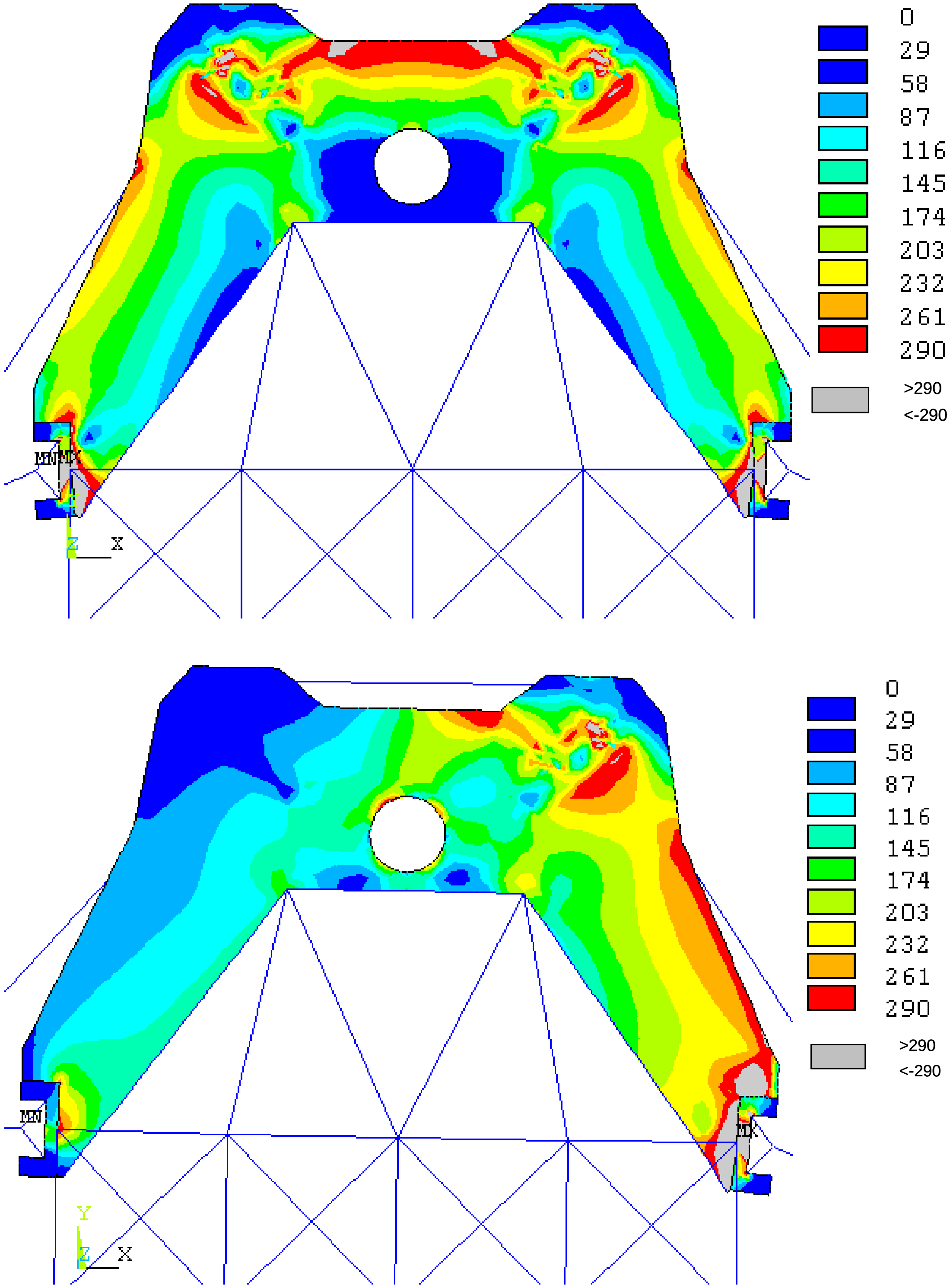


Fig.13: Stress field for the Von Mises Yielding Criteria for Vsd = 1050 KN, adopting for the frame plates a 12 mm thickness: on the top, symmetric case, on the bottom, asymmetric case; in gray are enlightened the regions where yield is reached.

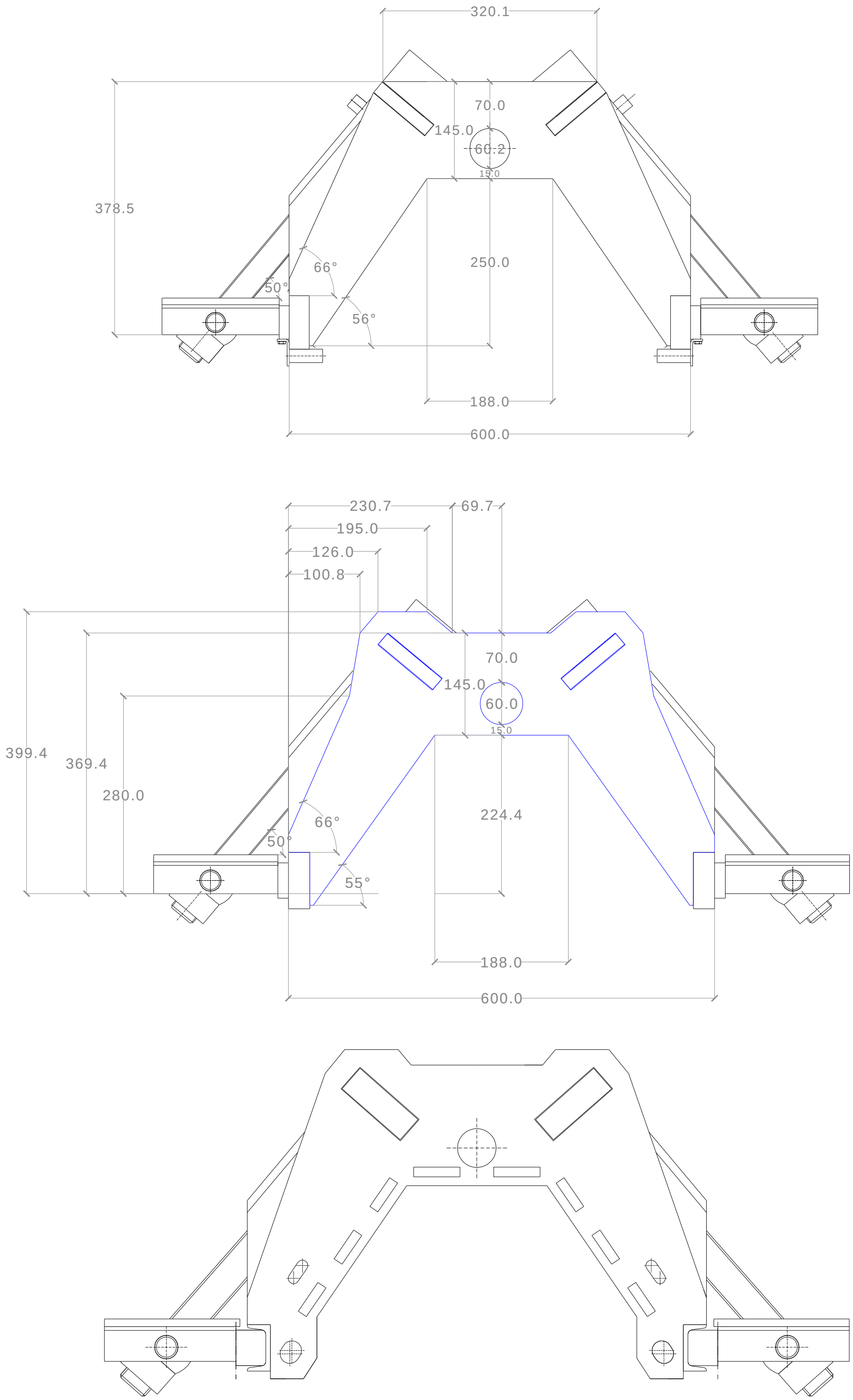


Fig.14: Evolution of the configuration of the cable-stayed bracket as consequences of the development of the analysis.

FULL THREE DIMENSIONAL MODELING

There are aspects of this connection that must be investigated and verified by a full three-dimensional modeling. Associated with this representation of the structural problem are the following considerations:

1. even if today there are powerful tools able to deal the geometric complexity, there are always limits of understanding a non planar problem;
2. the three-dimensional nonlinear analysis of concrete parts, with concentrated disposition of bars, is still today non robust; and there are few commercial codes able to do this kind of analysis with reliability;
3. there are plenty of proposed three-dimensional constitutive laws, that still have deficiencies: in the following, one will present results obtained by the simple but dependable Drucker-Prager failure criteria, associated with a linear elastic behavior until failure (3);
4. numerical failure to obtain the solution can be not related to true collapse of the real structure, but due to numerical difficulties like very marginal material crisis.

Fig.15 shows some aspects of the finite element modeling. Interesting aspects to inspect are:

1. the stress state of the core concrete just under the bottom plate of the frame;
2. the stress state of the plates around the holes devised to obtain a plain mechanical way of composition of the whole frame;
3. the stress state of the *C* device part that receive the trust from the external bracket;
4. the perturbation of stress state in the concrete column due to the presence of a vertical hole to permit the presence of a conduct for the water due to rain.

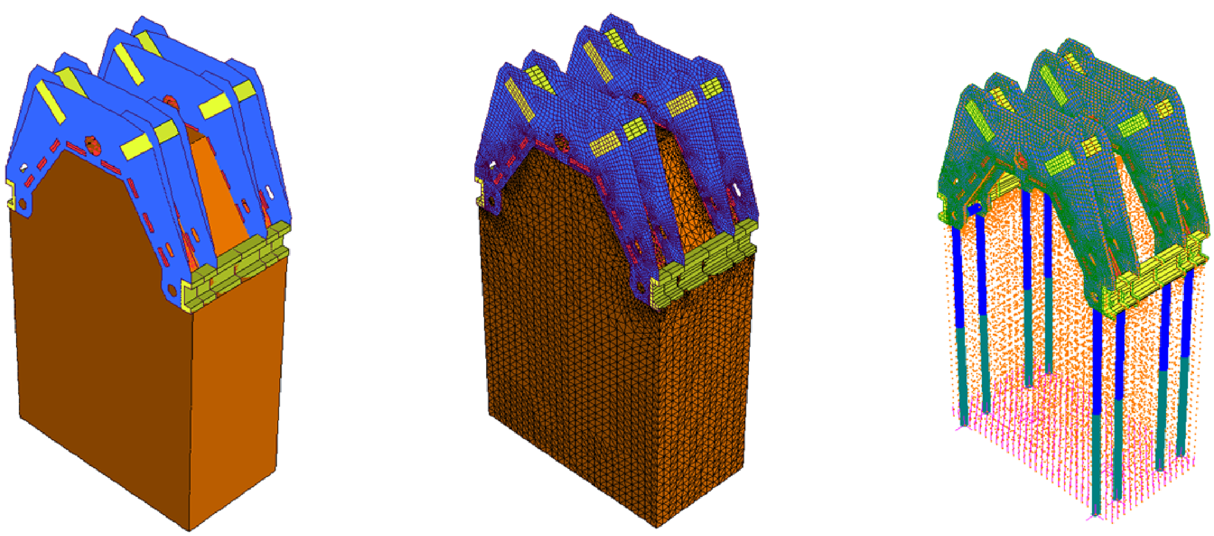


Fig.15: Three-dimensional modeling of the connection and of the segment of concrete columns; on the left, only the steel parts (plates of the frame and longitudinal bars) are represented.

Fig.16 shows the richness of the results that can be obtained by this comprehensive level of modeling. There, one has stress contours respectively for:

1. concrete mass;
2. vertical steel plates of the frame;
3. bottom steel plates of the frame;
4. C device part for the connection with the external bracket.

It is interesting to note, with gray color, the presence of limited crushed zones of concrete around the intersection of the vertical steel plates: in fact, one of the reasons to develop a three-dimensional model was to explore the possibility that these plates act as blade, cutting the concrete. Fortunately, this kind of failure was excluded on the basis of these and others results.

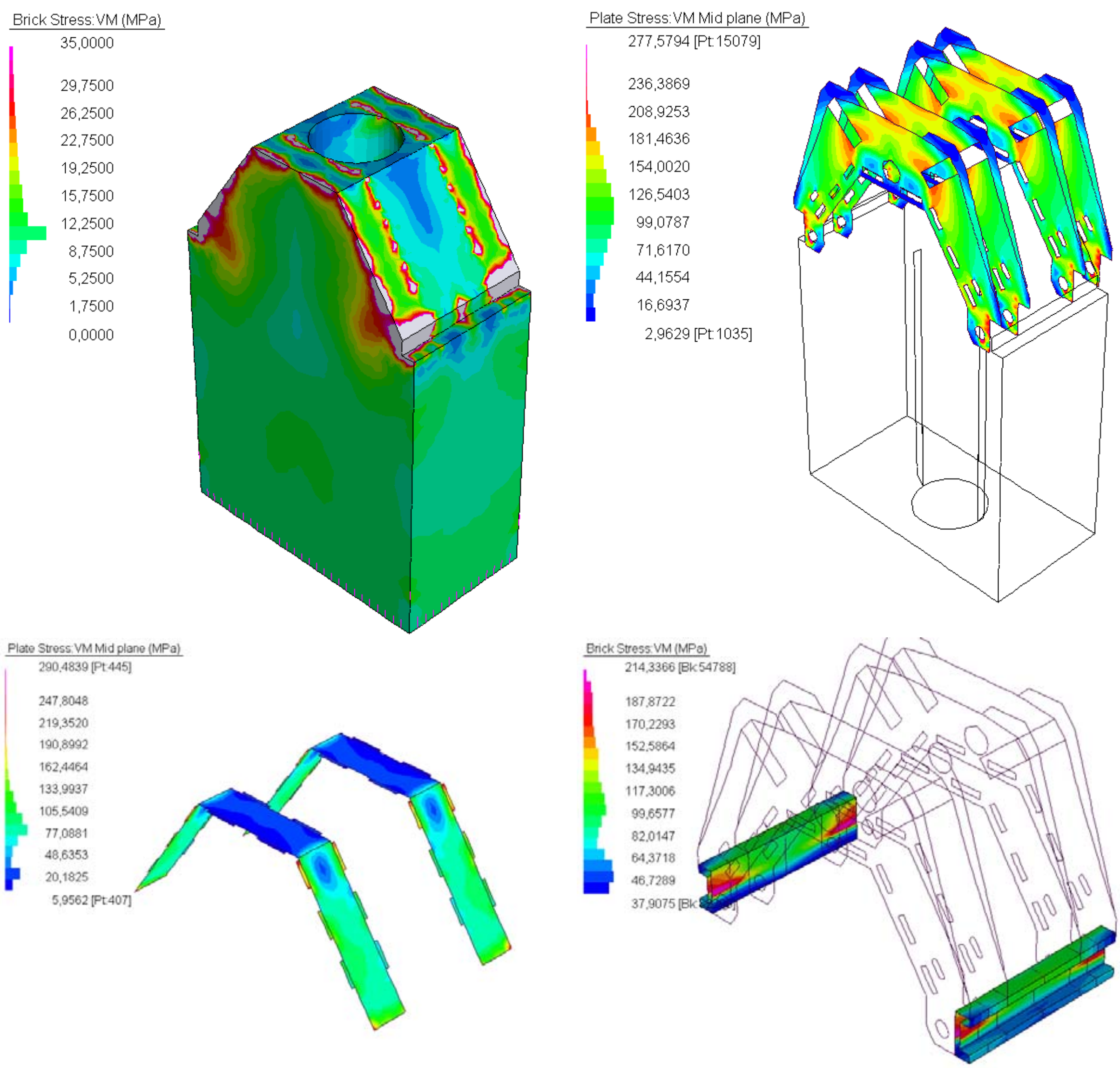


Fig.16: Stress contour obtained from three-dimensional analysis.

EXTERNAL PART

After having explored and defined the overall behavior of this innovative cable-stayed connection, essentially by S&T and mixed models, exanimate by detailed three-dimensional modeling specific aspects, it remains to optimize the external part, i.e. the bracket.
Fig.17 shows schematically the original arrangement of this piece and a typical stress state: one recognize specifically the two stays, the horizontal articulated joint, and the support plate with the four ribs.
Design criteria for this apparently small but critical component are the following:

- need to avoid the articulated joint made by special nickel-chrome based steel;
- need to reach a more compact configuration of this external part;
- need to help the constructability;
- need to reduce the weight of the piece, originally around *200 N*.

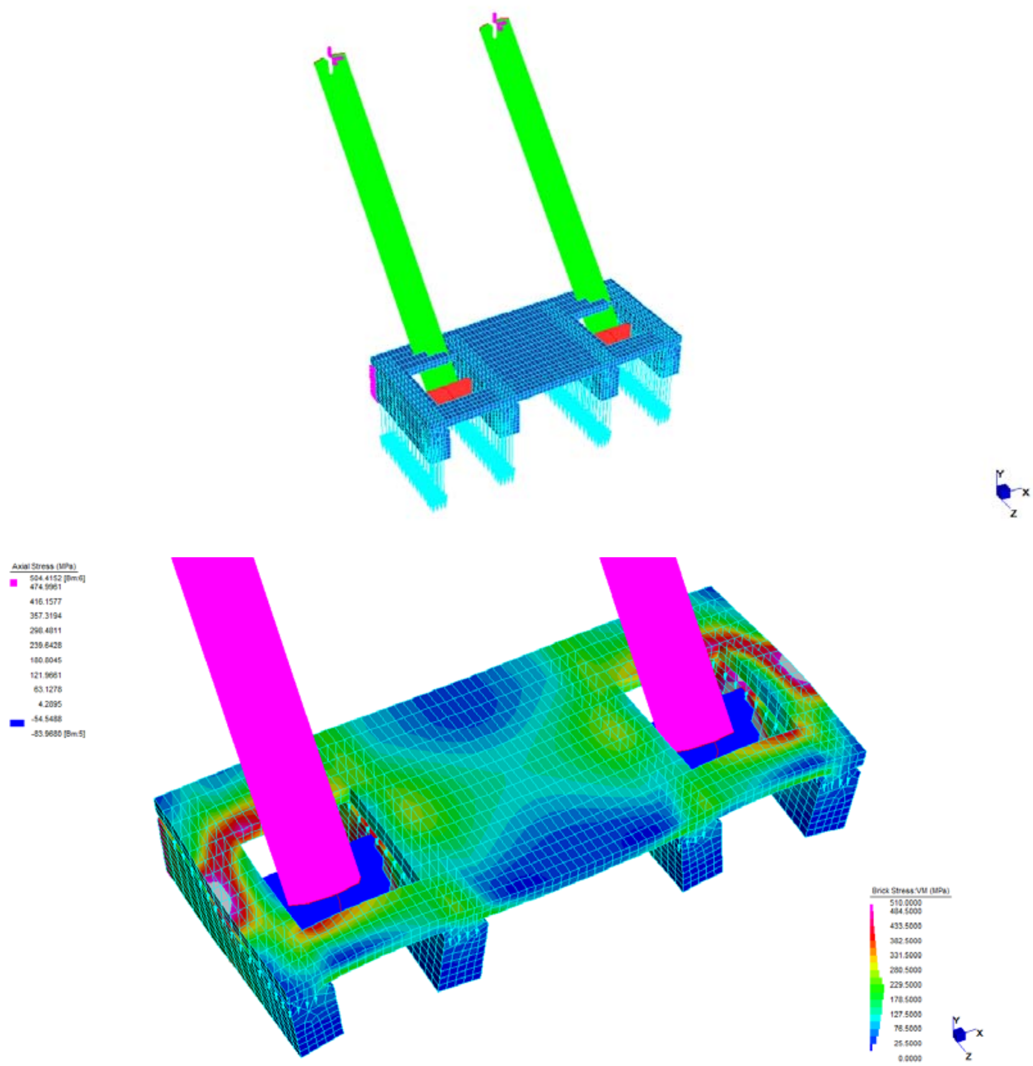


Fig.17: Initial configuration of the external part of the cable-stayed connection and, on the bottom, typical stress state after load application.

Fig.18 shows a refined configuration of the bracket initially proposed, by which one try to satisfy the design need before just expressed. It is worth to note the trend to pass from a traditionally composed element to a mechanical unitary piece obtained directly by fusion. This piece appears in fact more similar to a piece of an engine than similar to a piece of civil structural engineering.

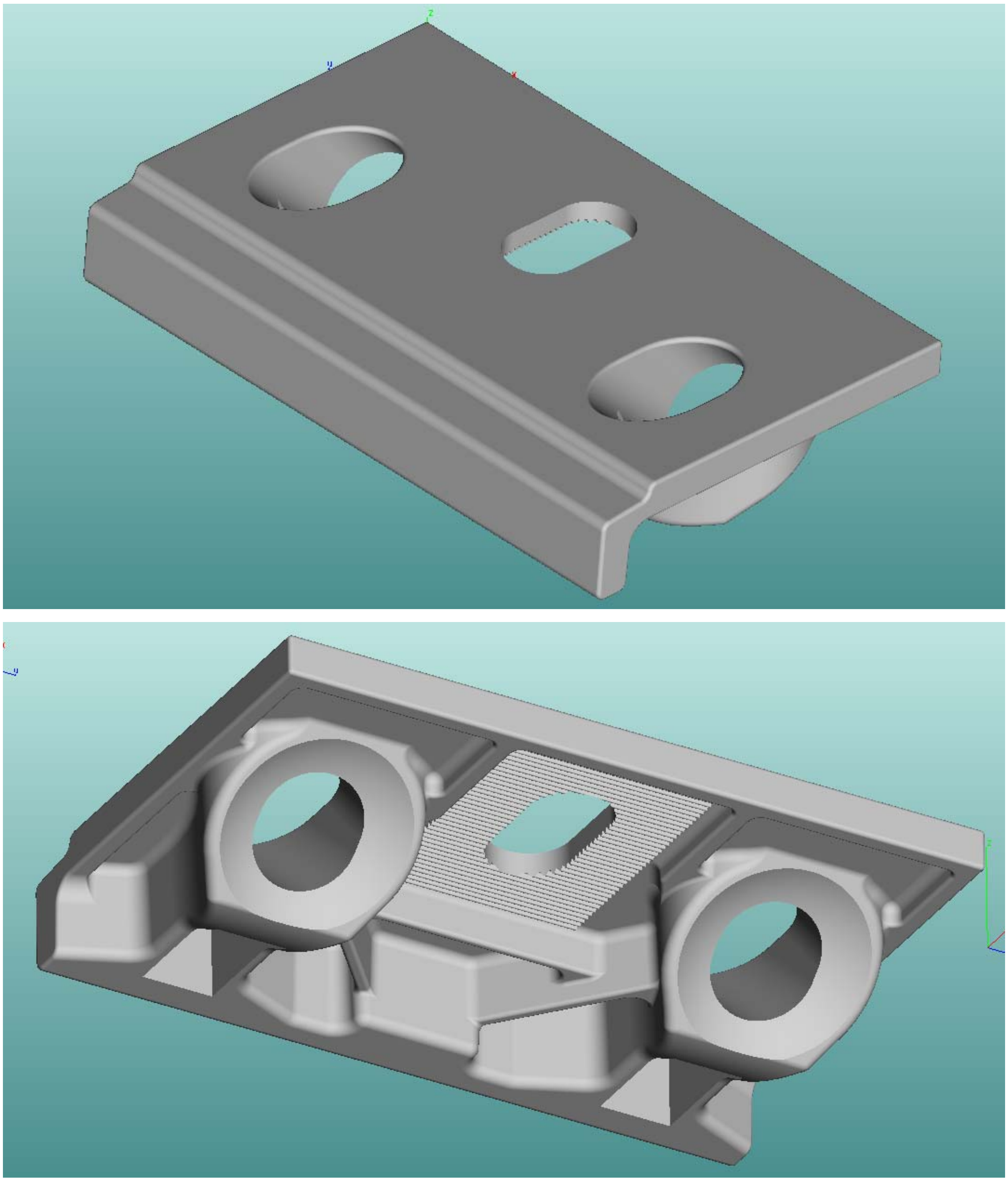


Fig.18: Top and bottom view of the initially proposed configuration of the external bracket.

To validate the proposal shown in Fig.18, specific analyses were of course developed. Also here, the main character is the unavoidable necessity to develop a solid representation of the external bracket. Of course, for this small connection parts, one easily reach some hundreds of thousands of finite element working in elastic-plastic field.
Fig.19 show the typical results obtained, in this case for a combination of loads that represent not only gravity based ones, but also possible horizontal seismic actions: by white color, one marks the yielded steel parts of the bracket.
At the end, Fig.20 shows the final fully optimized configuration of the external bracket: it is interesting to strict compare the geometry of Fig.18 and the one of Fig.20, to distinguish the change due to the optimization process.

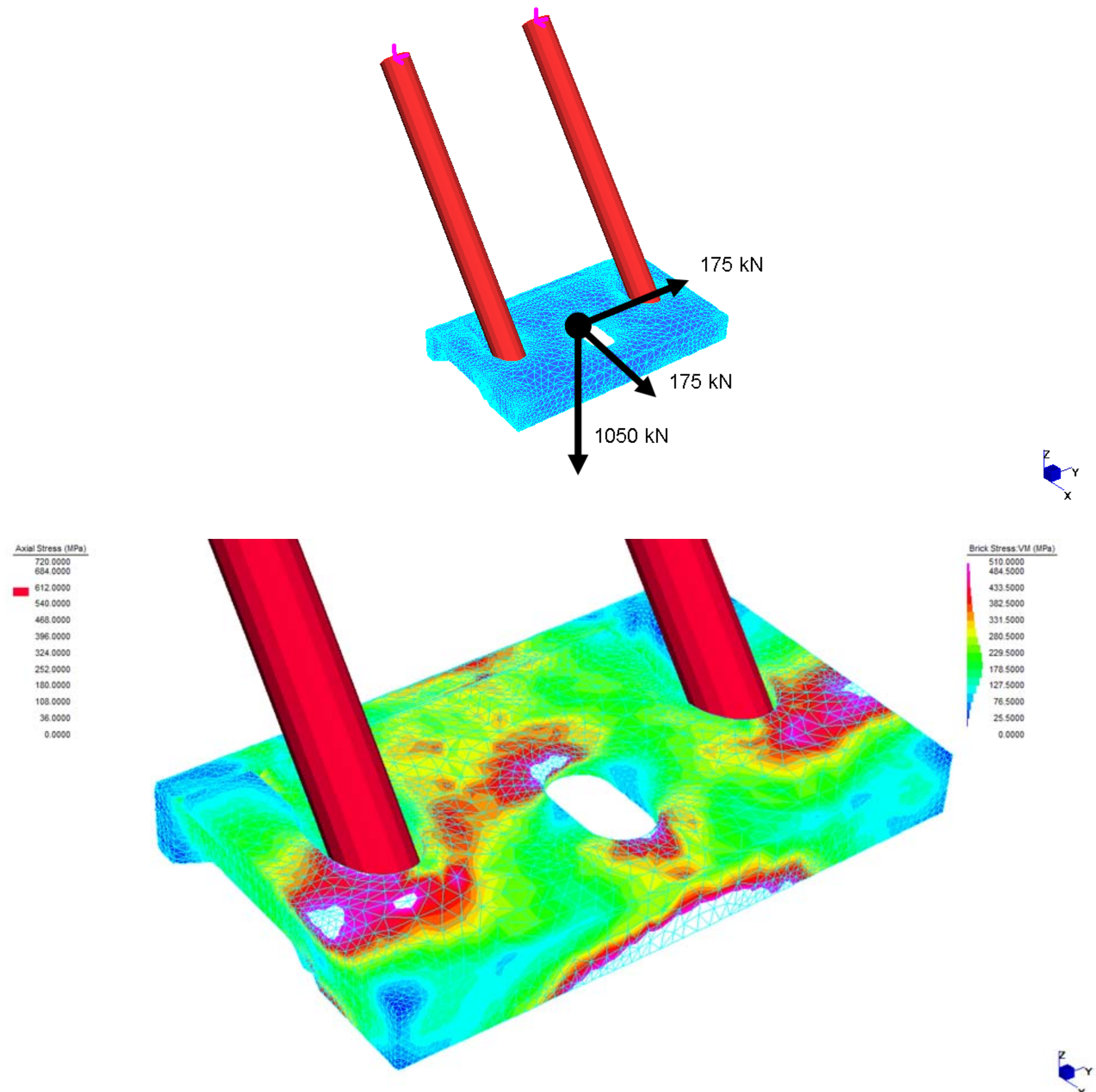


Fig.19: Typical load configuration considered and stress state contour obtained during the optimization process of the external bracket.

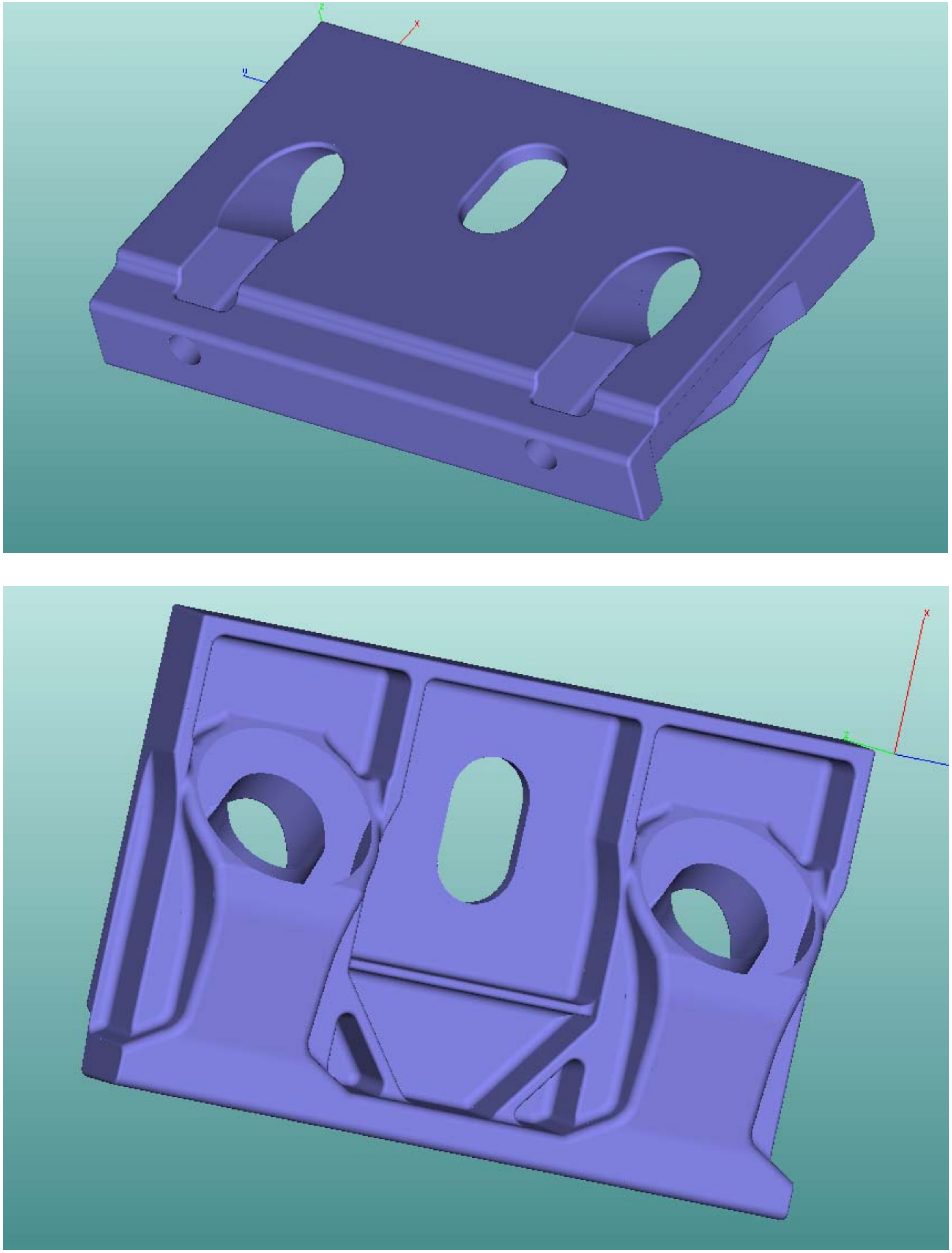


Fig.20: Top and bottom view of the finally obtained configuration of the external bracket.

CONCLUSION

In these last years, the design of precast structural elements has remarkably changed showing very sophisticated approaches to allow satisfying all the compound requirements of modern constructions. Of course the method of design and the tools supporting design must be capable to support these requirements.
Specific problems are connected with architectural and esthetically driven requirements which lead to a strong search for compact and minimal configurations of structural parts like brackets. At the same time, also the structural response must be optimized with regards to functional and ultimate responses but also with respect to structural robustness aspects.
Just robustness seems the most active field of application, to avoid disproportionate failures and progressive collapse. To this aim, contingency scenarios presenting damages should be always introduced and analyzed.
Furthermore, the possibility to include also dissipative devices is considered: connections are changing to very complex device to assure and control the structural behavior.
In the present work, the evolution of the design of a bracket component, supported by a cable-stayed system, is presented. This apparently simple element conceals a rather complex structural geometry, developed to be suitable both for strength requirements and constructability. This devised solution can assure:

- Manufacturing of precast elements without exterior parts;
- Minimal size of the bracket and completely hidden insertion in the supported beams;
- Compliance with different standards.

The evolution of the leading concepts and of the geometry of this element is explained together with the numerical analysis obtained both by synthetic models, like strut & tie, and by full non linear finite element models.
It is just the experience of the whole story of the evolution of this innovative cable-stayed bracket that, in the opinion of the authors, is important to reflect on.

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