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DESIGN OF STEEL AND COMPOSITE STRUCTURES WITH LIMITED DUCTILITY REQUIREMENTS FOR OPTIMIZED PERFORMANCES IN MODERATE EARTHQUAKE AREAS – THE "MEAKADO" PROJECT

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Abstract: The purpose of the present contribution is to summarize the developments carried out in the framework of the research project MEAKADO funded by European Commission. The aim of this research program is to develop specific design methodologies for steel and steel-concrete composite structures in regions characterised by a low to moderate seismic activity. The precise objective consists in looking for an intermediate way of designing in which a reduced but controlled amount of ductility is accounted for, providing thus the necessary safety required for allowing facing the uncertainties on the seismic action, but where the requirements are less stringent than a pure application of EC8-DCM design principles. The research program focuses on moment-resisting and concentrically braced frames. It covers a combination of experimental and numerical studies and is expected to result in proposals formulated according to a pre-standard format in the perspective of further revisions of the design codes.

Introduction

Even in the most advanced seismic design methods (like performance-based design), the general philosophy is always based on the assumption of global and fully developed plastic mechanisms whatever the seismicity level, together with the corresponding capacity design principles. The strict application of these principles for designing steel and steel-concrete composite structures in regions of low to moderate seismicity is however clearly leading to solutions that are on one hand rather difficult to implement and on the other hand often resulting in a significant increase of the building costs. As consequence, for economy reasons, it is often decided to design on the base of q=1,5 only (DCL design) and to neglect any further provisions aiming at enhancing the seismic performance, a practice which, from a safety point of view, cannot always lead to satisfactory structural solutions.

The aim of the running research program MEAKADO, summarized in this paper, is therefore to study design options with requirements proportioned to the actual seismic context of constructions in areas characterized by a low or moderate seismic hazard, contrary to most researches aiming at maximizing the seismic performances. More precisely the objective is to propose design rules that are optimised for the actual seismic action, providing the necessary safety level without imposing excessive requirements, and thus limiting the incremental complexity and costs associated with anti-seismic design. In other words, it is looked at trying relaxing some of the most constraining rules of the DCM design approach of EC8 (e.g. restriction on the use of cross-section classes, homogeneity of the overstrength over the entire height of the building…), having in mind that, for region of low to moderate

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seismicity (Germany, France, Belgium, parts of Italy…) characterized PGA ranging from 0.06 to 0.15 g, the optimal choice of behaviour factor is often about 2 rather than close to the maximum value allowed by the code.

The research MEAKADO has chosen to focus essentially on concentrically braced frames (CBF) and moment resisting frames (MRF), as being the most relevant typologies in the European construction market. Frames with dissipative eccentric bracing or other anti-seismic configurations (damping devices, isolators…) are of scarce relevance for low-to-medium seismicity areas.

Having these fundamentals in mind, an extensive literature review (see list of reference in Degee et al., 2015) actually shows out that, by studying in detail the results and achievements of previous works related to seismic performance of steel and composite structures, three types of research can be identified:

1. Fundamental research aiming at the improvement of background knowledge on material, members and structures behaviour in cyclic/seismic conditions. The main outcomes are models and relations allowing an improved prediction of the seismic performance in detail and globally;
2. Experimental and numerical studies on various structural typologies aiming at the verification and validation of behaviour factors. The focus is set on the optimisation of structures targeting the highest achievable behaviour factors;
3. Investigation of the seismic behaviour of particular products or application fields (e.g. cold formed profiles, sheeting, low rise residential or commercial buildings). The outcomes are performance characteristics evaluated having in mind the objective of maximising seismic resistance for each particular solutions.

This analysis shows out that most publications in the field of earthquake engineering is essentially carried out for applications in regions exhibiting a very significant seismicity level, with the aim of preventing brittle collapses and maximizing the capacities in terms of energy dissipation. Many outcomes of the past researches have been included in the most recent seismic design codes following the concept of q-factors related to the highest achievable ductility.

General methodology of the MEAKADO Project

The targeted objective of the research action is to study an intermediate way of design in which reduced but controlled amount of ductility is accounted for, providing thus the necessary safety with respect to uncertainties on the seismic action, but where the local ductility and structural homogeneity requirements are less stringent than for DCM in order to focus on intermediate values of behaviour factors. These requirements should be tuned according to the actual seismicity level of the area. Two main directions are followed to target the announced objectives.

The first one consists in the exploitation of phenomena that are known to contribute to energy dissipation in steel structures subjected to earthquake, but whose knowledge is not yet sufficient to quantify them as sources of controlled energy dissipation in the definition of the q-factors. So phenomena such as:

- Slip in bolted connections;
- Plastic ovalization of bolt holes;
- Post-buckling strength of diagonals in compression;
- Energy dissipation capacity in beams with class 3 and 4 cross-sections,

will be considered in the research and investigated either by means of experimental tests or numerical simulations in order to quantify the energy dissipation that they can provide and to adjust consequently the values of corresponding q factors.

The second direction consists in an investigation on the possibilities of tuning EC8 design rules given for DCM to the actual seismicity zone and to the targeted behaviour factor. The research focuses on moment resisting frames and concentrically braced frames, as being the most common configurations in practice. The following DCM-EC8 design rules are being re-considered, mainly on the base of numerical simulation tools calibrated and validated by the experimental campaigns.

- For DCM, if q is higher than 2, currently only class 1 and 2 profiles may be used in the dissipative zones of MRF. The possible use of class 3 (and even class 4) could be considered if the ductility demand is limited and an appropriate resistance level considering post-critical behaviour is considered.
- Rotation capacity of moment connections in MRF must currently be higher than 25 mrad for DCM. Smaller values could be allowed in case of limited overall ductility demand.
- In MRF, the ratio of the sum of column resistances to the sum of beam resistances at any structural node must always be higher than 1.3. This criterion will be reconsidered either regarding the value of the limit or the number and location of nodes where it has to be fulfilled.
- For braced structures, slenderness of diagonals must remain within a limited interval, limiting consequently the type of profiles that can be used for seismic bracings. Boundaries of this interval will be reconsidered. Another possibility could be to impose these restrictions only on a limited number of storeys.
- The overstrength coefficient (ratio between seismic demand and cross-section resistance) of diagonal bracings must not vary of more than 25% all over the height of the entire building. The limit of 25% as well as the number of storeys on which the variation has to be limited will be reconsidered.
- Horizontal displacements of the structure under earthquake action must be limited in such a way that the so-called sensitivity coefficient $\theta = P \cdot d_r / V \cdot h$ (P-Δ effects) remains smaller than 0.2 (or 0.3 if non-linear analysis is used). For MRF, this limitation is generally severe; for low seismic actions V (which is the denominator) the condition becomes even much more rigorous. In the case of limited ductility demand, higher values could be allowed in particular when major part of the structure remain elastic which under dynamic action means an immediate reversing of the deformations. It will be investigated if the limitation of the sensitivity factor is really relevant for the collapse limit state.

All the above parameters are planned to be studied first separately then in combination.

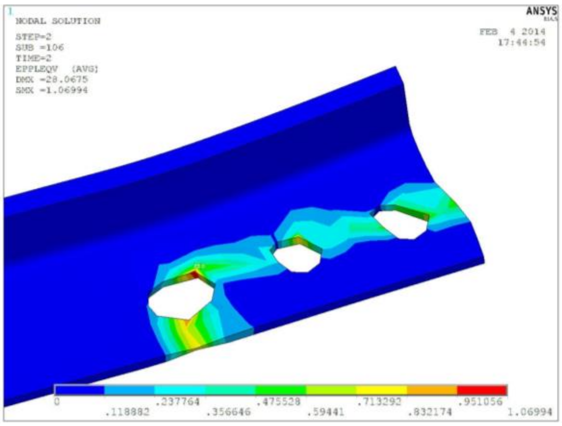
The main expected deliverable is a set of recommendations that could be included in the next revision of Eurocode 8 and that would allow better tuned design of steel structures in low-to-moderate seismicity areas, aiming at ensuring the adequate reliability level, improving the economic competitiveness and simplifying the design practice where possible.

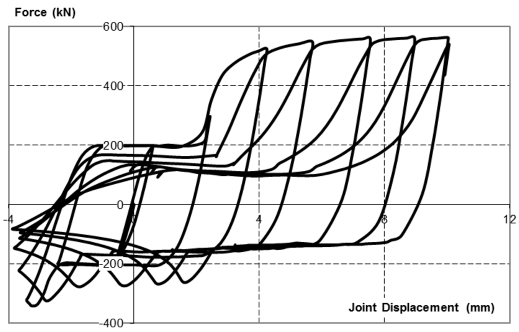
Assessment of energy dissipation in shear bolted connections

Developments carried out in this direction include implementation of a numerical model for bolted connections as well as the design on the experimental campaign to be carried out by Tecnalia.

The numerical model has been implemented using the finite element code ANSYS V.14 using brick elements, with a refined mesh in the zone of a the joint (see Figures 7.1.a and 7.1.b). Contact elements are used between bracing and gusset and between bolts and gusset/bracing, with isotropic Coulomb law to reproduce sliding and sticking (friction coefficient of 0.2). Clearance of holes and pre-stressing of the bolts are also considered. Material law is elastic plastic (Von Mises yielding criterion) with kinematic hardening.

The model has been used to perform static analysis, buckling analysis and fully non-linear analysis assuming an initial imperfection homothetic to the first buckling mode with amplitude of L/150, L being the length of the member. This model allowed identifying the possible failure modes (bolts in shear, failure in net section in tension, brace buckling in compression, block-shear in tension…) and the sensitivity of the specimens to variation of geometrical and material parameters and will help in interpreting the experimental results. Figures 1 illustrate some of the most typical failure modes numerically identified and the corresponding cyclic curves obtained with the model.





Failure by block-shear / Dissipation by sliding and yielding

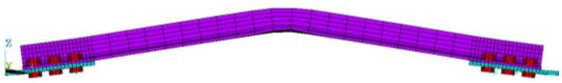


Figure 1. Typical numerical results on bolted connections

The planned experimental work consists in 30 cyclic tests on shear connections, representing the connections of the bracing system, varying key factors like the loading rate, the thicknesses of the gusset, the steel profile of the diagonals, the size, number and pre-stressing of the bolts and the surface state of both the gusset and the element. A detailed design report including the exact geometries is available. The objective is to identify how all these parameters contribute to the energy dissipation by means of the hysteretic behaviour developed in the connection, which accumulates energy by plastic deformation cycle by cycle until rupture.

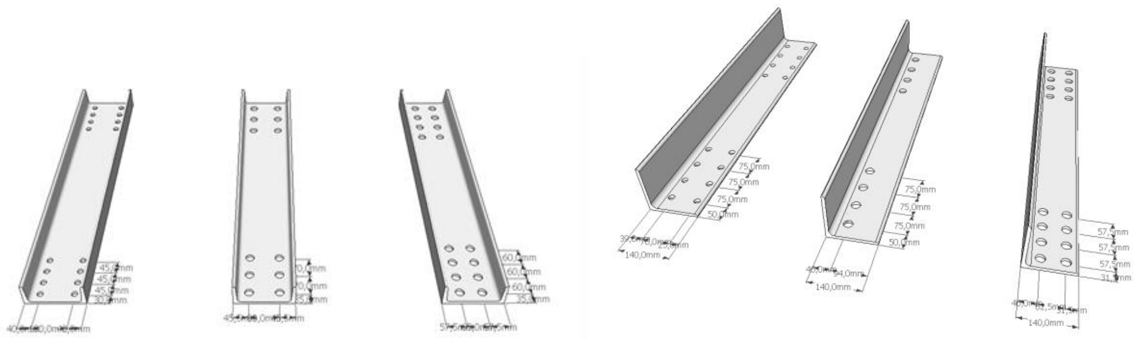


Figure 2. Test specimens for steel bolted connections

At the moment of finalizing this paper, the tests are in progress and results should be disseminated in the very next months. The testing method follows the classical ECCS procedure. Steel sections are selected among the set of braces obtained from global analyses of CBF case-studies presented later in the paper. Two sections are kept for further testing:

- UPN 180 channel, with cross-section area of 2800 mm²
- L 140x140x9 angle, with cross-section area of 2460 mm²

Three types of bolted connections are respectively considered for the channel (Types 1 to 3) and for the angle (types 4 to 6), as illustrated on Figure 2.

Cyclic behaviour of class 3 and 4 steel sections

This part of the research program also considers numerical and experimental investigations. At the moment of finalizing the present, 5 typical sub-structures selected among the different configurations studied numerically have just been tested at the laboratory of RWTH Aachen. The results will be processed in a near future.

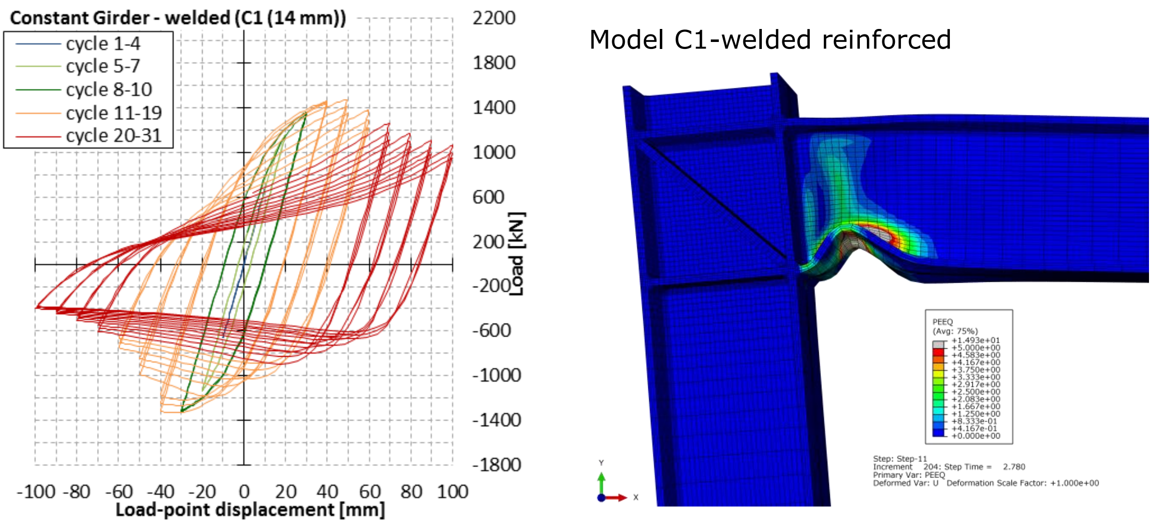


Figure 3. Typical results of MRF nodes with class 3 and 4 beams

Prior to the physical testing, a total of 24 cyclic simulations were carried out. Each type of frame corner was investigated with four different thicknesses of flanges as well as with reinforced and unreinforced panel zone. For type C (corner) both connection types were applied (welded and bolted) while for type H (haunched) only welded connections were used. Typical numerical results in terms of cyclic load-displacement curves referring to the point of load application as well as deformed shapes showing the accumulated plastic strains at the end of the loading history are illustrated for Model C1-welded at Figure 3.

Behaviour of concentrically braced frames under moderate seismic action

The methodology proposed for re-considering DCM-EC8 design rules for DCM in low to moderate seismic zones can be summarized as follows.

Step 1: Analysis of requirements

- Analysis of requirements and demands according to the current version of Eurocode 8 (with additional comparison to other codes US, NZ... if useful) with the purpose of identifying:

- Inherent demands and requirement, unconditionally necessary for the provision of satisfactory seismic performance and safety (usually requirements where the decision about their application can be either "yes" or "no")
- Gradual requirements, necessary mainly for the provision of dissipative behaviour (i.e. requirements which can be graded depending on the target dissipation, usually given by numerical values or defined as "to be applied to all details and members...")
- Interdependencies between the requirements (some requirements can be only satisfied if other conditions are also met).

Step 2: Relation between performance and requirements
Analysis of the relation between the requirements and the performance characteristics, in particular with regard to the dissipated energy (absolute energy amount as well as energy amount relative to the elastic energy)

Step 3: Time-history simulations
Use of numerical simulations (time-history dynamic analysis) for determining the actual demands of the set of typical structures designed according to Eurocode 8 or with relaxed requirements, depending on the amplitude of the seismic action and on the duration of the seismic action. The latter has not been clearly considered up to now, although there is a strong dependency of the demands on dissipative details or members on the number of cycles to be sustained by the structure or member without damage. Numerical simulations will be performed using artificial and natural time-histories as input data in order to get a realistic assessment of the duration and consequent amplitudes and number of cycles.

Step 4: Analysis of results
Evaluation of the numerical simulations with regard to the gradual requirements defined in step 1, e.g.:

- Number, distribution and sequence of yielding in the bracings;
- Depth of plastic deformation;
- Corresponding influence of 2nd order theory effects and damage limitation (based on total and inter-storey drifts);
- Energy dissipation required for a given value of target behaviour factor;
- Possible grading of requirements based on the identified demands.

Step 5: Alternative dissipating mechanisms

- Identification of alternative dissipating mechanisms satisfying the reduced demands for low to moderate seismicity, e.g. connections in shear (yielding of bearing holes, friction...), use of class 3 and 4 cross-sections, consideration of the compressed diagonal.

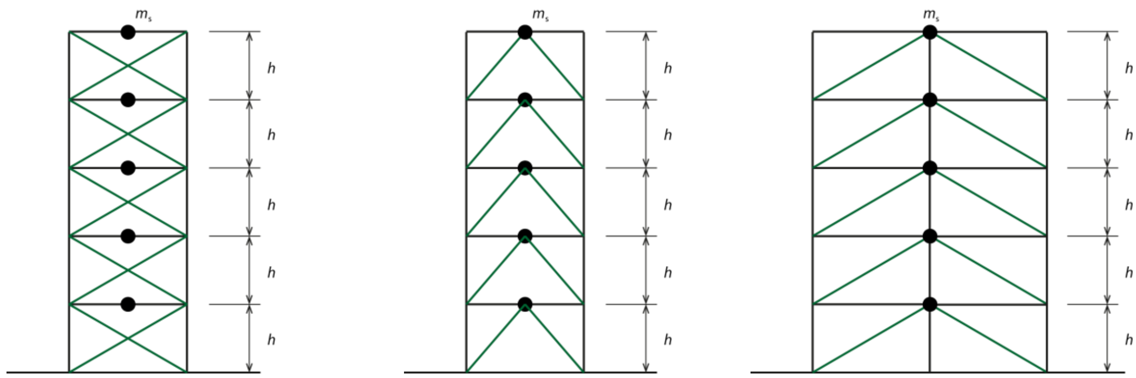


Figure 4. CBF configurations considered within Meakado

This methodology requires of course the preliminary design of reference case-studies, as well as an automatic design tool allowing easily redesigning and optimizing the structures when the EC8 criteria are totally or partially released. Such a tool has been prepared by CTICM for the 3 structural configurations presented at Figure 4, including the possibility to vary the number of storeys.

Perspectives

Based on the development already carried out at this stage, the next steps planned in the research program are the followings:

- Finalization of the tests on shear connections and processing of the results;
- Continuation of the numerical analyses on shear connections based on the experimental results;
- Processing of the experimental tests on class 3 and 4 steel cross-section;
- Numerical and experimental study of class 3 composite sections;
- Finalization of the numerical parameter investigations on CBF according to the methodology presented above;
- Execution of a work on MRF similar to the one currently in progress for CBF, starting by the elaboration of a set of case-studies designed according to EC8.

This work intends to lead to first effective conclusions on the behaviour of CBF and MRF in situation of moderate seismic demand, in the perspective of optimizing their design. These suggestions for updated design rules in low and moderate seismicity areas are planned to be available by mid-2016. Moreover, specific pushover and shake-table tests will be carried out at the very end of the project to demonstrate and validate the updated design rules that will be suggested.

Conclusion

The objective of the present contribution has been to communicate the perspectives open by the running European Research Programme MEAKADO in terms of optimized seismic design of steel structures in moderate seismicity areas. At the moment of finalizing this paper, no definitive conclusions can of course be drawn yet from the developments, but the corpus of results is promising and should allow coming out with very interesting conclusions at the end of the funded period of the project by the end of 2016.

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