EUROPEAN RESEARCH AND CODE DEVELOPMENTS ON SEISMIC DESIGN OF COMPOSITE STEEL CONCRETE STRUCTURES

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SUMMARY

Composite steel concrete moment frames are structures for which design guidelines for earthquake resistance are poor worldwide. This is due to the fact that experimental research on such structures was, until very recently, considering only the case of vertical loading, while, under horizontal loading the response of the structure is very different since; in particular, positive bending moments can appear at the beam ends. In order to solve the problems raised by the seismic design of these structures, the European Union has promoted a huge research effort. It involves experimental activity in several large European testing installations. Programs have been run on shaking tables at Bristol, Athens and Bergamo. One huge test of a full scale 3 D structures, 3 storey high and 3 bays by 3 bays in plan has been run at the Elsa facility of the European joint research Centre at Ispra. One plane frame was tested at Saclay. The experimental data have been processed and numerical modelling developed. Design guidelines, based on the results obtained, are prepared. They will be included in the revised version of Eurocode 8 [CEN, 1998] now under way. The main features of the research efforts and of the code developments are set forward in this paper.

INTRODUCTION

Up to now, the seismic design of composite steel concrete structures leaves the designer in front of many questions for which no convincing answers or minimal guidance exist. The behaviour of composite moment frames in recent earthquakes was sometimes bad. Some reasons are to be found on the steel material and welding side, but specific composite aspects of the elements and structures behaviour probably contributed.

Composite constructions can correspond to many different structural typologies or systems, as long as concrete and steel are combined. The complete understanding of all aspects of the seismic behaviour of all types of composite structure requires years of research efforts. Recent developments in the U.S. have been bearing on composite moment frames with partial strength connections and on composite systems combining concrete walls or columns with steel or composite beams. In Europe, recent research work has been focused on moment frame structures with rigid connections.

Two main design options exist for such frames:

- either the composite behaviour of beams at their connections to the columns is neglected; then, the design can be based on the properties of the beams steel sections only; however, this requires a proper disconnection of the slab from the steel sections, because the capacity design of columns requires a safe (over) estimation of the plastic moments of beams.

- or it is taken advantage of the stiffness and plastic resistance of the composite beams; then, design data must be provided, which define the effective widths of beams (under positive and negative bending, for the elastic as well as the plastic parts of the local behaviour), the adequate sections and lay out of the

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rebars in the slab, the proportions of steel sections and slab which realise a ductile behaviour of the plastic hinges (classes of sections), the structural behaviour factors corresponding to these classes, some requirements on the type and number of connectors between steel and concrete, the stability checks for columns.

This second design option has been the main subject of the research efforts in Europe since 1996. These activities and their main results are summarised hereafter, as well as some original aspects of the design recommendations, which have been derived from these researches.

EXPERIMENTAL RESEARCH AND THEORETICAL DEVELOPMENTS

Dynamic tests on the ductility of composite beams at ISMES-Bergamo (I) [Plumier C. and Doneux, 1998]

In order to determine the condition to realise ductile composite steel-concrete section when these are submitted to seismic action three shaking table tests have been performed on composite steel-concrete simply supported beams. The composite sections were chosen to favour a failure by concrete plastic crushing taking into account the limitations of the shaking table. One important parameter to characterise the behaviour of these beams and their ductility at the design stage is the ultimate deformation of the concrete ε_{cu}, in dynamic cyclic conditions. This parameter ends out to be greater than the 2.10^{-3}, value given by Eurocode 2 for static design conditions, but it is smaller than the value given by the static concrete test. The ductility ratio of the composite beams, based on the mid-span vertical deflections values, is greater than 3.

The existence of relative sliding between steel and concrete brings damping. It has been evaluated and found greater than 15% at high level of acceleration (25-30 m/s²). A study on the influence of the degree of connection on the damping is needed to calibrate this effect. The steel-deck shape can influence the failure mode and the ductility. A study involving various steel-deck shapes is needed to evaluate this influence and to eventually forbid some shapes for the application to composite beams under seismic action.

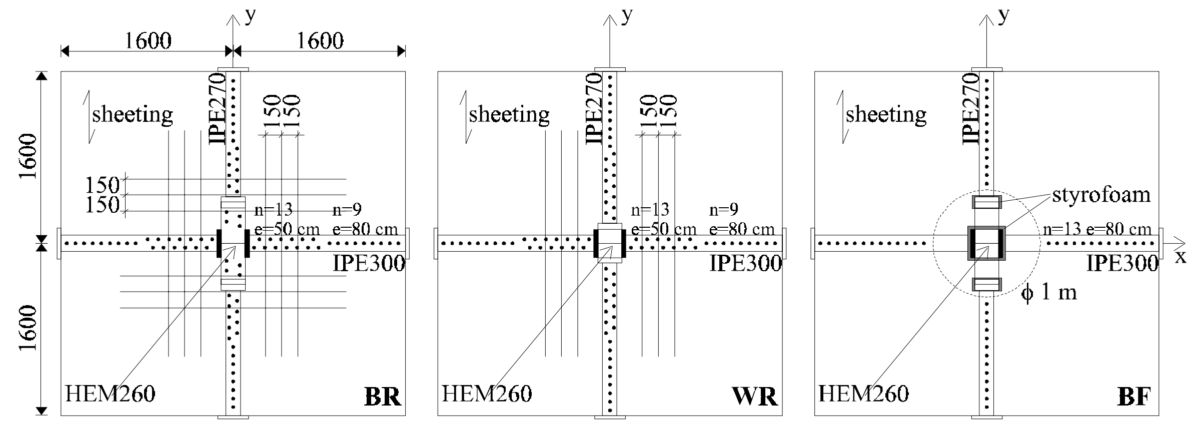

Figure 1: Slab reinforcements and connectors layout of specimens BR, WR and BF of Darmstadt test

Cyclic tests on beam-column sub-assemblages at Technical University of Darmstadt (D) [Doneux and Parung, 1998]

Three full-size interior composite beam-to-column joint assemblies of a composite building frame with floor slabs were tested under cyclic loading. The assemblies were partly designed with the current Eurocode 4 for composite structures under gravity loads. Several particular design concepts are tested, such as different layouts and concentration of studs and reinforcements, and the influence of a transverse beam in the composite beam-to-column moment force transfer. The specimens were highly instrumented.

The test program performed on joint sub-assemblages at Technical University of Darmstadt was part of a global research project, the three sub-assemblages being replicas of parts of a three-dimensional structure tested at the ELSA facility. This test is described hereafter. The main goal of the research project was to study the role of the slab on moment transfer in earthquake resistant composite frames. One practical conclusion can already be drawn from the tests on sub-assemblages: the design relations presented in Plumier et al. (1998) provided a safe design, realising the intended yielding scheme for values of bending moments close to the computed ones. However, the contribution of the slab and its behaviour, as a tension or compression flange of a beam carrying membrane forces is a complex phenomenon, which is still being deeper studied by developing a detailed non linear numerical model of the beam-column-slab connection zone. This model will be used to study into detail the influence of design on the moment rotation curves of such zones and derive practical data for designers, the experimental results being used to calibrate the model.

Bi-directional Cyclic testing of a 3-D Frame at the Joint Research Centre at Ispra (I) [Bouwkamp, Parung and Plumier, 1998] [Plumier, A, Doneux, Bouwkamp and Plumier, C, 1998]

To evaluate the feasibility of composite construction in earthquake-prone regions, a test of a full-scale structure has been run in the ELSA reaction-wall facility of the European Joint Research Centre at Ispra, Italy. The structure, a 3 storey 3 bay by 3 bay moment frame, has been conceived in order to test design hypothesis. It is an assembly of various zones characterised by variations of parameters like the density of devices connecting the slab to the beams, the density of the reinforcement of the slab, the proportions of the composite sections, the effectiveness of the stress transfer from the slab to the columns. From the test, moment rotation curves at every connection have been derived.

Considering these program objectives, the following specific test program has been executed:

Phase 1. Quasi-static cyclic loading in X-direction; max. top-floor displacement of +/- 180 mm (2%),

Phase 2. Quasi-static cyclic loading in Y-direction as in phase 1,

Phase 3. Quasi-static cyclic loading with following bi-directional loading: induce and hold Y-directional displacement of 90 mm and follow with X-directional loading of 2 cycles of +/- 90 mm. Repeat procedure for Y-X displacements of 180mm.

Phase 4. Pseudo Dynamic Test

Phase 5. Quasi-static cyclic loading in X-direction until failure; max. top-floor displ. of +/- 400 mm (4.5%)

The comparison of the behaviour of the different zones allows useful conclusions.

- the design relations of the reinforcements of the slab of composite beams gave a layout that maintained the intended integrity of the concrete during the cyclic testing.

- the effective widths of slab deduced from Eurocode 4 [CEN, 1994] provide correct estimates of the real plastic moments of composite beams. Paulay's definition of effective width gives slightly better results.

- for capacity design purposes, the plastic moments must be computed taking into account all the re-bars present, welded mesh and simple re-bars.

- considering the steel sections only in the design of composite frames is totally inaccurate; it is also unsafe for what concerns the capacity design of columns.

- disconnecting the slab from the beams ends and from the columns in a narrow zone does not prevent bending moments higher than those of the steel sections to be realised in the plastic hinges.

Parallel to the experimental studies of the beam-column assemblages at the TU Darmstadt and the 3-D frame at ELSA, Ispra, extensive numerical correlative studies have been performed with the software DRAIN-2D. The beam to-column connection zones at either end of the beams were modelled as linear-non-linear fibre models capable of capturing the non-linear cyclic response of the composite beams in those regions. Numerical results, using the DRAIN-2DX computer program, show excellent agreement with the experimental results. Considering the test performance of the 3-D frame and the excellent correlation with numerical results, the composite moment resistant structure would perform well under an actual design earthquake. In fact, using the Ballio method to determine the behaviour factor q, the results for the test frame without styrofoam around the columns and a thickness of the slab of 15 cm, indicated a q factor of 4.5 (at a top floor displacement of 21.6 cm), columns and beams being modelled as steel and, respectively, composite linear beam-column elements.

Figure 2: View of tested 3-D frame in front of reaction wall at ELSA facility

Shaking table tests on beam-column sub-assemblages at Athens Polytecnics (GR)

To evaluate the difference in responses between cyclic quasi static and real dynamic tests, beam-column sub-assemblages have been tested on the shaking table at the University of Athens. Two shear interactions have been considered. The tests also provided data on the low cycle fatigue resistance of the headed studs connecting the steel sections and the concrete: it was demonstrated that an the low cycle fatigue resistance may be the critical aspect of design once partial shear connection is realised.

Low cycle fatigue test of a plane composite frame at CEA Saclay (F)

A 3 bay plane composite frame has been tested under constant amplitude of displacements at the CEA Saclay. The parameters considered are the degree of shear connection between steel and concrete and an original detailing of the connection between slab and facade steel beam. See Figure 3c. The test intended to set forward the peculiar aspects of behaviour of composite beams in low cycle fatigue and to study the redistribution of bending moments during the applied force reversals as well as to provide the usual data on elastic stiffness and plastic resistances of beams of different design. The tests concluded to the efficiency of the new design detail and provided data from which effective widths have been derived.

Shaking table tests for the experimental evaluation of behaviour factors at Bristol University (UK) [Tsujii, Elnashai and Broderick, 1999].

A series of tests have been dedicated to the experimental evaluation of behaviour factors of composite steel concrete structures. A comparison of the composite frames with bare steel frames was conducted. This study, coupled with numerical dynamic analysis using the ADAPTIC software, came to the conclusion that behaviour factors of the composite frames were slightly larger than that of the bare steel frame, while higher values of overstrength and dynamic ductility were also observed. In parallel, other purely numerical work was also done in order to handle better the context of the behaviour factors of composite structures. In particular, a study was dedicated to the definition of the correct way to evaluate q factors, because it had appeared that in past studies many different definitions of such critical parameters as “first yield” or “plastic redistribution factor” had been used, sometimes bringing apparent high discrepancies in results, which in fact were only related to the methodology. [Sanchez and Plumier, 1999]

Cyclic tests on connectors at INSA Rennes (F) [Aribert and Lachal, 1999]

Data on the cyclic behaviour of the connectors are very poor. An extensive research work on headed studs and on cold-formed HILTI connectors has been realised at INSA Rennes. It consists in a large series of shear tests on connectors and a limited number of tests on beam column connections. It concludes with design data and the general observation that partial shear connection corresponds to an early degradation of the connectors.

SOME FEATURES OF THE EUROPEAN DESIGN RECOMMANDATIONS

General content

The European design recommendations deal with the following structural types: concentrically and eccentrically braced frames, reinforced concrete walls or columns with steel or composite beams, encased steel plates working as shear walls and moment resisting frames classified “braced” or “non sway” according to the criteria:

$$\theta = \frac{P_{tot}.dr}{V_{tot}.h} \leq 0{,}10 \qquad (1)$$

In this relationship, d_r is the horizontal displacement at the top of the storey, relative to the bottom of the storey, h is the storey height, V_{tot} is the total horizontal reaction at the bottom of the storey and P_{tot} is the total vertical reaction at the bottom of the storey.

Earthquake resistant composite buildings can be designed according to one of the following concepts:

Concept a Dissipative structural behaviour with composite dissipative zones.

Concept b Dissipative structural behaviour with steel dissipative zones.

Concept c Non-dissipative structural behaviour.

In concepts a and b, the capability of parts of the structure called dissipative zones to resist earthquake actions out of their elastic range is taken into account. When using the design spectrum, the behaviour factor q is taken greater than 1,0.

In concept b, structures are not meant to take any advantage of composite behaviour in dissipative zones; the application of concept b is conditioned by a strict compliance to positive measures that prevent involvement of the concrete in the resistance of dissipative zones; then the composite structure is designed to Eurocode 4 under vertical loads and to the chapter on steel structures of Eurocode 8 to resist earthquake action, but the problem is to define the positive measures preventing the involvement of the concrete.

In non dissipative structures (concept c), the action effects are calculated on the basis of an elastic analysis without taking into account non-linear material behaviour, but considering the reduction in moment of inertia brought by the cracking of concrete in part of beam spans. This is achieved by using two different moment of inertia I1 and I2 with a specific distribution.

The European proposal defines design criteria, design objectives and design rules. Design criteria are general objectives expressed in general terms not related to one particular typology of structures and aiming at the development of structures dissipating as much energy as possible; they are similar to those defined for steel or concrete structures. A design objective is one particular global mechanical behaviour, which, for one particular typology of structure, allows the design criteria to be reached. Design rules are mathematically well defined checks which, for one typology of structures, express local conditions (in connections zones, in elements) necessary to comply with the design objective.

Design of members

Low strength concrete (class lower than C20/25 for instance) should not be used, because of its brittle character, and its inadequate properties for composite work. Reinforcing steel considered in the plastic resistance of dissipative zones should be ductile; this apply to bars and to welded meshes; however, welded meshes not complying with ductility requirements may be used in dissipative zones, but the sections of reinforcement in the mesh must then be duplicated by ductile reinforcements. The problem behind this statement is that a reliable negative plastic moment in the connection zone can only be based on the presence of reinforcements guaranteed ductile, while the beam plastic moment considered in the capacity design of column must include all possible contributions of the reinforcement, non ductile welded mesh included, for instance.

For what concerns the steel sections, it is prescribed that the members in which dissipative zones are located must be made of sections belonging to a class of cross sections defined in Eurocode 4 and related to the behaviour factor of the structure as follows: class 1 for $q > 4$, class 2 for $1.5 < q \leq 4$ and class 3 for $q \leq 1.5$, while all the members part of the earthquake resisting structure should belong to the class 1 or 2. It can be shown that for composite T beams this means that the section A_s of the rebars present in the effective width of slab should be small, so that they yield under the plastic negative bending moment.

For beams in which dissipative zones are located, the design must achieve a ductile behaviour in bending. Under positive bending moment, the integrity of the concrete is maintained during the seismic event and yielding takes place in the bottom part of the steel sections. This goal can only be achieved with the presence of fixed transverse beams with shear connectors. Under negative bending moment, the neutral axis should not be positioned too high, in order to avoid excessive slenderness of the compressed portion of web. As mentioned above, this objective corresponds to an upper limitation of the section A_s of the rebars present in the slab.

Because partial shear connections correspond to early local failure in the connectors or in the concrete around the connectors, it is prescribed that beams must be designed for a minimum of 80% of a full shear connection.

To achieve ductility in plastic hinges, it is prescribed that the distance from the concrete compression fibre to the plastic neutral axis should not be more than 15 % of the overall depth of the composite cross section. This is the Eurocode 4 rule aiming at the development of extensive yielding in the bottom flange of the steel section when the beam is submitted to positive moments.

For beams with slab in which dissipative zones are located, specific reinforcements of the slab called "seismic rebars" must be present in the zones of connections of the beams to the columns. Their sections A_s and their lay out must be designed to reach ductility. It has been established that there cannot be one simple single rule which would guarantee that this goal is achieved. In fact, the design is different for exterior and interior columns; it is also different when beams transverse to those primarily bent by the earthquake action are, or not, present, that is when beams are present, or not, on two orthogonal axis directions at their connections to the columns. This has led to the definition of an “Annex j” on slab design in the connection zones [Doneux and Plumier, 1999].

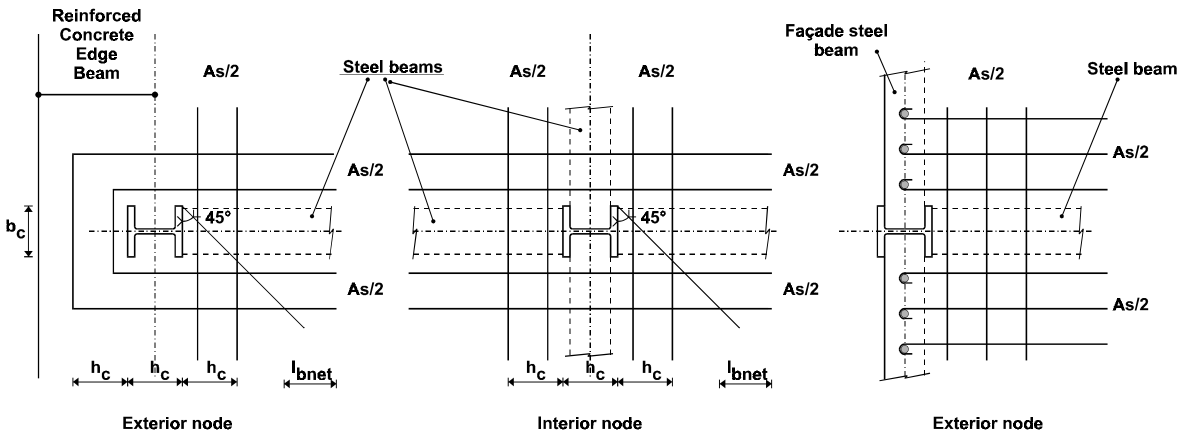

Figure 3: Layout of "Seismic Rebars

Effective Width of slabs

The effective width of slab to be used in the determination of the elastic and plastic properties of the composite T sections made of a steel section connected to a slab are defined in Table 1 and Figure 4; these values are valid when the seismic rebars defined in the “Annex j” are present.

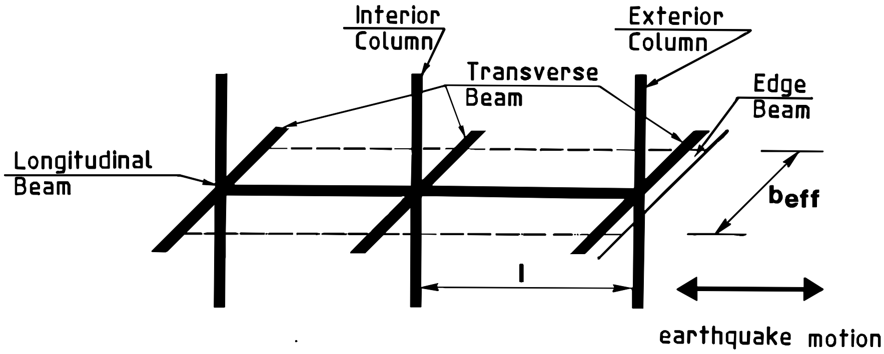

Figure 4: Definition of Elements in Moment Frame Structures

Table 1: Definition of effective width of slab

b_{eff}	Transverse beam	b_{eff} for M_{Rd} (PLASTIC)	b_{eff} for I (ELASTIC)
At interior column	Present, fixed to the column, with connectors for full shear	For M^- : 0,2 ℓ , For M^+ : 0,15 ℓ < transverse slab span	0,1 ℓ 0,075 ℓ
At interior column	Not present, or present and not fixed to the column, or not having connectors for full shear	no proposal	no proposal
At exterior column	Present as an edge beam fixed to the column - in the plane of the columns, with connectors for full shear and specific detailing for anchorage of rebars - exterior to the column plane, with rebars of the hair pin type	For M^- : 0,2 ℓ , For M^+ : 0,15 ℓ < transverse slab span	0,1 ℓ 0,075 ℓ
At exterior column	Not present or no rebars anchored	For M^- : 0 For M^+ : b_c or h_c	0 $b_c/2$ or $h_c/2$

Analysis of structures

In moment frames, the plastic resistance of a composite section can be computed considering only the steel section, if the slab is totally disconnected from the steel frame in a circular zone around a column of diameter $2b_{eff}$, b_{eff} being the greater of the effective width of the beams connected to that column.

Total disconnection means no contact between slab and any vertical side of steel element (columns, shear connectors, connecting plates, corrugated flange, omega steeldeck nailed to the flange of steel section, …).

For a dynamic elastic analysis of the structure under earthquake action, the stiffness I1 of composite sections in which the concrete is in compression is computed considering the effective concrete section and a modular ratio $n = E_a / E_c = 7$.

The stiffness I2 of composite sections in which the concrete is in tension is computed considering that the concrete is cracked and that only the steel parts of the section are active.

The structure is analysed considering the presence of concrete in compression in some zones and in tension in other zones. In beams of moment frames for instance, an equivalent moment of inertia is defined:

$$I_{eq} = 0.6 I_1 + 0.4 I_2 \qquad (2)$$

Plastic Resistance of Dissipative Zones

Two plastic resistances of dissipative zones are considered in the design of composite steel concrete structures: a lower bound plastic resistance (index p ℓ , Rd) and an upper bound plastic resistance (index u, Rd).

The lower bound plastic resistance of dissipative zones is the one considered in design checks concerning sections of dissipative elements. Example: $M_{p\ell,Rd} < M_{Sd}$. The lower bound plastic resistance of dissipative zones is computed considering only the steel components of the section which are ductile.

The upper bound plastic resistance of dissipative zones is the one considered in the capacity design of elements neighbour of the dissipative zones. Example: at the intersection of beams and columns of constant section, the design rule is: $1.2\,(M^{+}_{U,Rd,beam} + M^{-}_{U,Rd,beam}) \leq 2\,M_{p\ell,Rd,column}$. The upper bound plastic resistance is established considering all the steel components present in the section, including those which are not certified ductile.

CONCLUSIONS

A huge research effort has been made in Europe in the years 1996-1999 in order to develop design rules for composite steel concrete moment frames with rigid connections submitted to seismic action. This effort has been concluded in 2000 by the edition of a chapter on composite structures which will be included in Eurocode 8. This chapter covers other types of structures, for which U.S. or Japanese data and recommendations already provided wide data. The Eurocode 8 chapter on composite steel concrete structures provides the data required to make the classical elastic analysis of structures (spectral response and modal superposition) and to do substantiated capacity design checks of the connections and the columns, as needed in the standard designers' approach used in projects of buildings. Of course, these recommendations are based on a limited number of experiments and analysis, of which some are still under way, so that all cross checks from other researchers are particularly welcome.

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