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Experimental and Theoretical Study of Composite Connections

Étude expérimentale et théorique d'assemblages mixtes

Untersuchung über Verbindungen bei Verbundbauweise

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SUMMARY

This paper presents the main results of experimental research aimed at analysing the behaviour, up to collapse, of beam-to-column steel and concrete composite connections commonly used in practice. A simplified structural model for the prediction of the actual flexural behaviour is described and validated by comparison with experimental results. In addition, a non-linear finite element program for the analysis of composite frames with semi-rigid joints is presented.

RÉSUMÉ

Cet article présente les principaux résultats d'une recherche expérimentale dont le but était l'analyse, jusqu'à la ruine, d'assemblages mixtes acier-béton couramment utilisés dans la pratique. Un modèle structural de calcul destiné à prédire le comportement réel de ces assemblages soumis à flexion y est décrit; sa validité est démontrée au travers de comparaisons avec des résultats expérimentaux. Un programme de calcul non linéaire aux éléments finis pour l'analyse des structures mixtes à nœuds semi-rigides est enfin présenté.

ZUSAMMENFASSUNG

Dieser Bericht zeigt die wesentlichen Ergebnisse experimenteller Untersuchungen auf, die das Ziel hatten, das Verhalten von üblichen Riegel-Stützen-Verbindungen aus Stahl und in Verbundbauweise bis zum Grenzstand zu analysieren. Ein strukturell vereinfachtes Modell zur Vorhersage des Verformungsverhaltens wird beschrieben und die Gültigkeit durch Vergleich mit experimentellen Ergebnissen belegt. Schliesslich wird ein Finite-Elemente-Programm zur nicht-linearen Berechnung von Verbundkonstruktionen mit verformbaren Ausschlüssen vorgestellt.

1. SCOPE OF THE RESEARCH WORK

Economy in steel construction results much more from savings of labour cost than from savings of material. There is thus a trend in simplifying the detailing of joints with the consequence of a non-linear response of these joints in moment-relative rotation curves. In a beam-to-column semi-rigid joint, the relative rotation between beam and column axis is due to two contributions mainly. The first one deals with the *connection* properly (deformation of the fasteners and assembling accessories and of the column flange(s), possible slips because of hole clearances, local deformation of column web due to load introduction by the beam(s),...); the *shear deformation* of the column web panel in the vicinity of the joint is the second source of flexibility.

Much research work was conducted on bare steel framed joints with the result of a largely improved knowledge of the actual behaviour of such joints up to collapse. In contrast few information is available regarding composite joints. Therefore a recent research was launched in the Department MSM of the University of Liège with the financial help and guidance of ARBED Recherches (ECSC Research-agreement N° 7210-SA/507); it is first aimed at studying experimentally the behaviour and ultimate strength of joints between a bare steel column and composite girder(s) (steel beam section associated to a reinforced concrete slab by shear connectors) by means of web- and flange cleat(s) and 8.8 quality bolts, which were preloaded at a specified level corresponding to hand tightening (Fig. 1).

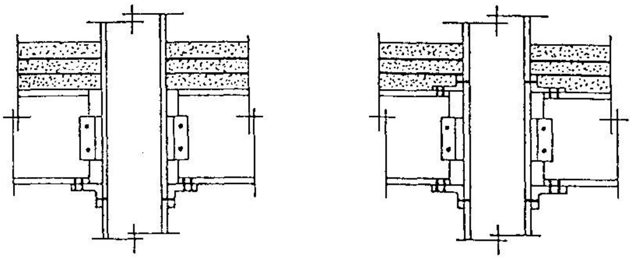


Figure 1 : Types composite joints tested in laboratory

Amongst the series of possible parameters, the following were selected because of paramount importance:
a) the relative beam-to-column flexural stiffness: a HEB 200 section column is connected successively to an IPE 240 - 300 - 360 section beam associated to a 12 cm thick RC slab ;
b) the rigidity of the assembling cleats: 150 x 90 mm angles are used with a thickness of 10 mm and 13 mm respectively ;
c) the presence or not of an upper flange cleat ;
d) the geometric proportion of reinforcements in the RC slab : 0.67 % (ϕ 10mm) - 1,3 % (ϕ 14 mm) - 2,1 % (ϕ 18 mm).

The symmetrical cruciform testing arrangement used to load the joints until collapse does not produce shear in the column web ; so the recorded experimental curves characterize only the deformability and the resistance of the composite connections.

All the test specimens were fully instrumed so that the individual components of the connection flexibility can be identified and measured, on the one hand, and that the force distribution in the assemblage be determined. Some tests were performed on full steel bare joints - i.e. without RC slabs - for sake of comparison.

The benefical influence of the stiffness and bending resistance of the joints on the performance of steel or composite frames requires the development of reliable methods for the prediction of the non-linear response of the joints and for the analysis of the frames. Present paper is only aimed at drawing the main conclusions and the critical appraisal of the acquired knowledge. The reader interested in knowing more about the test programme is begged to refer to [1, 2].

2. EXPERIMENTAL RESULTS

The experimental results were analysed and conclusions drawn regarding the interpretation of the test results in general terms, on the one hand, and the influence of the selected parameters, on the other hand.

2.1. General interpretation of the test results

General conclusions are dealing with the nature of collapse and the level of carrying capacity exhibited by the connections :

i) All the joints used partial-strength connections; the maximum moment is however an appreciable proportion - 65 to 100 % - of the plastic moment of the composite beam section.

ii) Collapse occurs either because of buckling of the lower beam flange (for IPE 240 sections), or because of buckling of the column web or yielding of the reinforcements in the RC slab according to the proportion of such reinforcements (for IPE 300 and 360 sections).

iii) Slip between the beam lower flange and the relevant cleat due to hole clearance contributes predominantly to the connection flexibility.

iv) There are two other possible sources of connection flexibility : the compressive strains in the column web in front of the beam lower flange and the axial deformation of the RC slab between the facing ends of the beams. Their respective contributions to the connection flexibility is highly dependent on the proportion of reinforcements.

2.2. Influence of the parameters

How the parameters are liable to influence both stiffness and resistance is reflected in comparative load-displacement plots (fig. 2, 3, 4 and 5) and can be summarized as follows :

i) The individual influences of the cleat thickness, of the number of flange cleats - 1 or 2 -, and of the proportion of reinforcements respectively, are qualitatively similar, whatever the beam section used.

ii) Any increase in the proportion of steel reinforcements for a specified steel connection configuration results in larger initial rotational stiffness and maximum bending capacity (fig. 2).

iii) The rotation capacity of the connections is linked to their collapse mode - yielding of rebars (fig. 3) or column web buckling (fig. 4 and 5) - which is highly dependent on the proportion of steel reinforcements in the slab (fig. 2).

iv) An increase of the cleat thickness - in the range of sizes available on the market - does not provide with a significative increase of both rotational stiffness and maximum bending capacity (fig. 3, 4 and 5).

v) An additional upper flange cleat is not liable to change appreciably the global behaviour of the connection (fig. 4 and 5), as far as collapse is not initiated by yielding of the reinforcements.
When collapse of joints is initiated by plastic deformations of the reinforcements(fig. 3), the upper flange cleat contributes to the transmission of the tensile force through the connection, with the result of an increased bending capacity, as far as there is some strength reserve in the part of the connection aimed at transmitting compressive forces.

3. MATHEMATICAL PREDICTION OF THE COMPOSITE CONNECTION BEHAVIOUR

The shear stud connectors, that are welded on the upper flanges of the steel beams in the experimentally tested composite joints, have been designed in order to obtain a full interaction between the steel members and the RC slabs. The resulting absence of slips allows to assume the in-plane indeformability of the end sections of the composite girders (fig. 6.a). The simplified structural model (fig. 6.b) which has been developed to predict theoretically the non-linear response of the connections is based on this assumption. This model consists in an infinitely rigid beam (the end section of the girders)

lying on an elastic-plastic foundation materialized by axial springs simulating respectively the deformation and the resistance :
- of the reinforcement bars ;
- of the concrete ;
- in the zone of the upper flange cleat, of the web cleat and of the lower flange cleat: bolts in shear, in tension and in bearing, column flange, column web, cleat, slips between cleat and steel beam, ovalization of bolt holes.

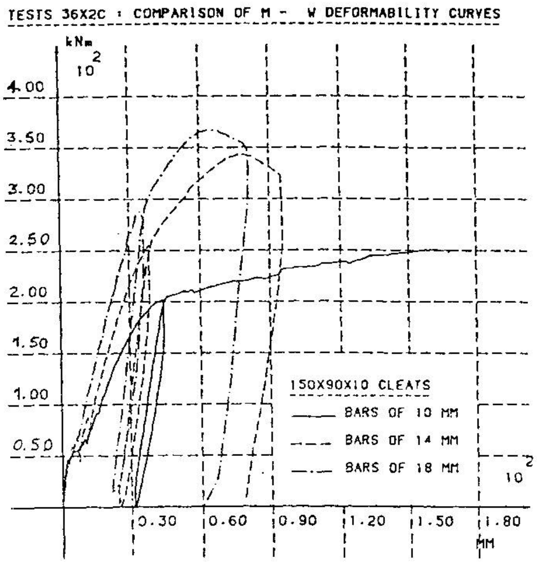


Figure 2 - Influence of the percentage of reinforcement in the concrete slab (connections with IPE 360 beams - no upper flange cleat)

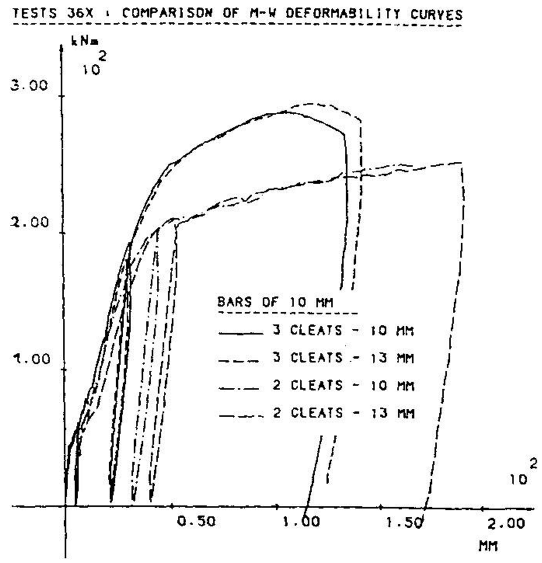


Figure 3 - Influence of cleat thickness and number of cleats-rebars of 10 mm (connections with IPE 360 beams)

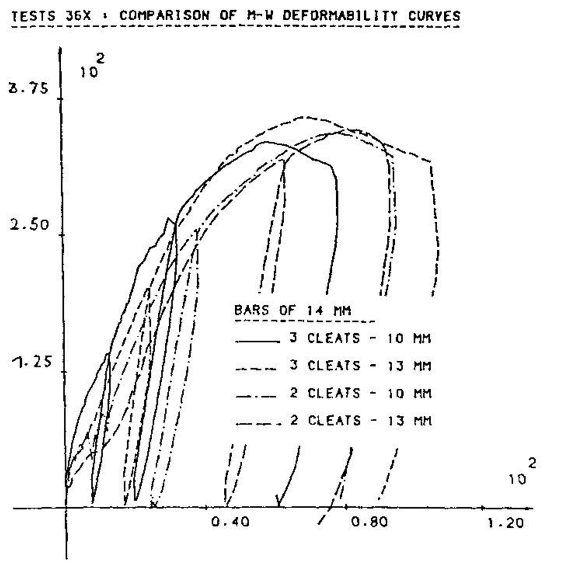


Figure 4 - ibidem - rebars of 14 mm.

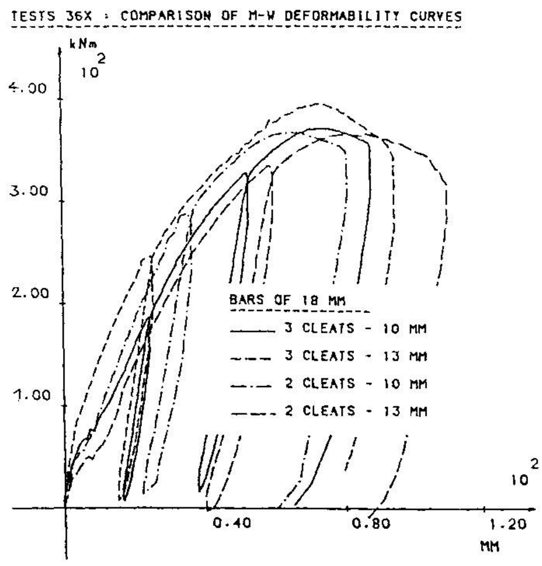
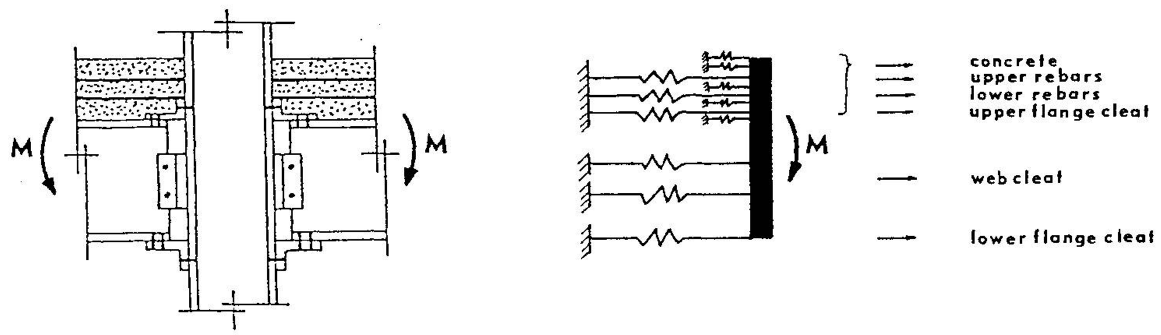


Figure 5 - ibidem - rebars of 18 mm.

Each of these springs is characterized by a specified non-linear force-displacements curve which has to be predicted as reliably as possible. Methods of modelling have been proposed for each source of deformability [2]. The introduction of concentrated loads into a column web has been particularly studied in [3].

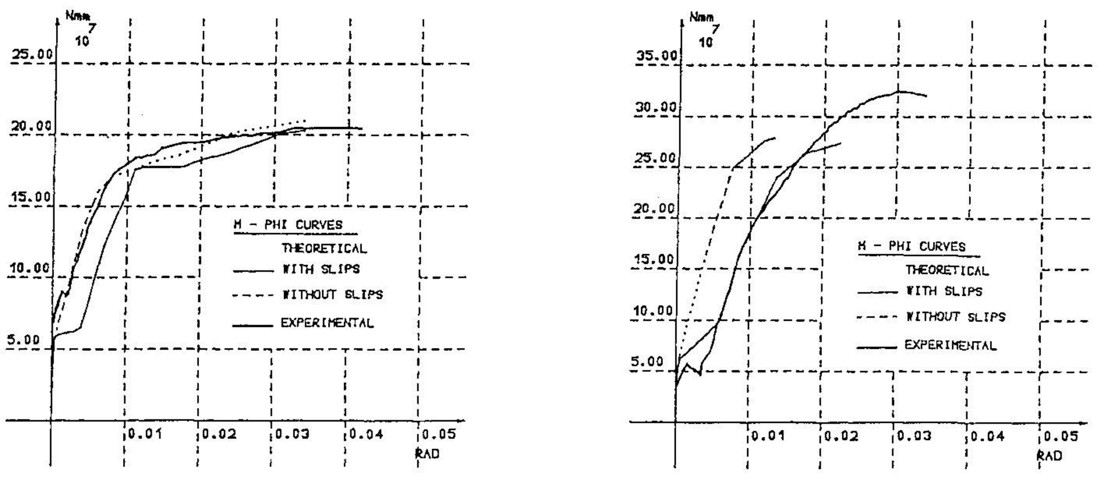
The moment-rotation curve corresponding to a particular composite connection is built up step by step by distributing, at each level of bending moment, the loads between the springs according to their actual relative stiffness and by evaluating the associated rotation of the infinitely rigid beam.



a) actual composite connection b) equivalent structural model

Figure 6 - Definition of the theoretical model for connection behaviour prediction.

This procedure has been applied in figure 7 to two composite connections only differentiated by the percentage of reinforcement.
According to the initial relative position of the bolts in their holes, the slip between the cleats and the beam may or not occur during the connection loading, what justifies the necessity to report two different theoretical curves corresponding respectively to the development of the maximum permissible slip (which depends to the hole clearances) and to the absence of slip. The influence of this parameter on the connection deformability is seen to be relatively significant.



a) rebars of 10 mm b) rebars of 18 mm

Figure 7 - Comparison between experimental results and the response of the equivalent structural model (composite girders with IPE 300 beams - no upper cleat - 150 x 90 x 13 cleats).

A close agreement between the experimental curve and the response of the theoretical model is obtained in the first example where the collapse corresponds to the yielding of the rebars, as well in the second one, except for what concerns the prediction of the ultimate resistance associated, in this case, to the buckling of the column web.
This safe but important divergence may be explained (see reference [3]) by the very low out-of-plane initial imperfection of the column web measured on the specimens tested in laboratory in comparison with that, choosen on base of rolling tolerances [4], which has been considered for the assessment of the theoretical buckling load of the web.

The interest of such an equivalent structural model is threefold :
- to validate the individual mathematical models developed for each source of flexibility of the composite connections : cleats, introduction of loads in column webs,...;
- to represent a valuable tool in view of intensive parametric studies ;
- to constitute a foundation for further developments of a more simplified and practical approach for the evaluation of the deformability and resistance characteristics of the composite connections.

4. ANALYSIS OF FRAMES WITH COMPOSITE JOINTS

The finite element program FINELG which is being developed at the University of Liège and at the Polytechnical Federal School of Lausanne gives the possibility of solving two types of problems. The former consists of the calculation of the critical loads and also of the associated buckling modes. The latter consists of following the non-linear evolution of a structure under increasing external loading up to collapse or instability, and even beyond. This program allows one to take account of great displacements, ,instability phenomena, non-linear constitutive laws of materials (steel, concrete,...), initial deformations, residual stresses,... The main finite elements of the FINELG program are the following : truss elements, plane or spatial beam elements, plane composite steel elements [5], plate-membrane elements, shell elements, linear constraint elements, non-linear spring elements.
The FINELG program has been modified so as to simulate the behaviour of semi-rigid connections [6] and of sheared column web panels [3]. The moment-rotation curves, characteristics of the actual behaviour of the joints, may be modelled by using more or less complicated mathematical laws (linear, bilinear and multilinear laws, power law, extended Richard's law, Ramberg-Osgood law,...).

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