STRUCTURAL CONNECTIONS. EXPERIMENTATION AS DESIGN TOOL

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In building frames, beam-to-column connections, beam splices and column bases are quite important structural elements, the rotational stiffness and the resistance of which strongly affect the frame behaviour. Their study has been however disregarded during many decades, most of the studies being devoted to the beam and column elements. Now the situation has changed and an intensive research activity is carried out since ten to twelve years on structural connections. Thousands of experimental tests have so been carried out on connections, on sub-frames including connections and - really few - on whole frames. In the present paper, different aspects of this experimental activity are highlighted on the basis of the experience got in Liège through more than 120 tests on connections and sub-frames. In addition the paper describes the way in which experimentation can be integrated into the research strategy in view of the development of design tools for practice.

INTRODUCTION

Steel frames for buildings have usually been designed on the basis that the beam-to-column connections in bending are either pinned or rigid. The actual stiffness though will fall somewhere between these extremes, giving what is generally termed "semi-rigid" behaviour. In particular, a connection may also have a resistance which is less than that of the connected beam; such behaviour is termed "partial strength".

Clearly the stiffness of the connections, and their resistance, will influence the response of the frame as a whole. It is now widely recognised that steel frames can be deliberately designed as "semi-continuous", on the basis of semi-rigid and/or partial strength behaviour.

This approach provides greater freedom than the usual procedures, with the connections being chosen by the designer to meet the particular requirements of the structure. This often results in a decrease of the total weight of the structure or of the fabrication and erection costs. The resulting savings may amounts 5 to 20 % of the total cost of the frame [4].

To get the benefits of semi-rigid design, calculation models for the evaluation of the stiffness and resistance properties of the joints have to be made available to designers. Such models are analytical ones; they have to be validated through comparisons with experiments carried out in laboratories.

The number of possible connection detailings and loadings justifies that thousands of tests have been performed in the past, are still in progress nowadays or are planned for the future. In the recent years, some different attempts to collect the results of these tests in computerized databases have been initiated. One of the more widely agreed databases nowadays in Europe is SERICON [1].

In the next pages, different aspects related to the experimentation on connections and to the use of test results in research and practice are discussed.

WHY TO PERFORM TESTS ON CONNECTIONS, SUB-FRAMES AND FRAMES?

As said before, the stiffness and resistance properties of the connections are required for frame analysis and design. These properties can be obtained through experimentation carried out on full scale connections tested in isolation or as part as a sub-frame or of a whole frame. The next step consists in gathering all the tests performed at the international level in a databank as SERICON. The database is then made available to the designers in view of its use in the frame of specific projects. This procedure seems attractive at first sight but is not the one which should be recommended, because of the unavoidable differences - loading conditions, steel grades for steel and bolts, frame effect,... - between the connections tested in laboratory and those considered in the actual project. Some of these points will be discussed in the next pages.

A much more efficient way consists in the development of analytical models allowing to predict mathematically the stiffness and resistance properties of the connections. These models have to be able to adapt themselves to the required loading conditions or to the variation in the mechanical and geometrical characteristics of any of the connection elements.

In Liège, such models have been proposed for strong axis steel beam-to-column joints and beam splices [7]. They have widely been used as references in the preparation of the new revised Annex J on "Joints in building frames" of Eurocode 3 [2]. At present models for composite joints and column bases are in development.

The research strategy when developing these design tools is the following.

- Results of available experiments are used to validate numerical finite element (FEM) models.
- FEM models are used to perform parametric studies allowing to understand better the connection response and to point out the influence of the main significant parameters.
- Based on this knowledge, analytical tools aimed at predicting the connection response in terms of stiffness, resistance and deformation capacity are developed.
- These analytical tools are finally validated by means of comparisons with experimental results contained in the databases and coming from different institutions so to ensure a wide recognition to the proposed model.

This technique is far more better than that based on curve fitting, the range of application of which is rather limited and often not clearly specified.

The models resulting from such research works can then be simplified before making them available to designers. Annex J of Eurocode 3 [2] is the result of such a simplification process; it can be used as a reference document but remains however rather complicated to apply in a hand calculation. Further simplifications have therefore been achieved in the frame of a recent SPRINT project [3], in the frame of which simple design sheets, design tables and softwares have been produced. Such design tools really allow the designers to benefite from the semi-rigid concept without increasing the calculation costs.

EXPERIMENTATION ON FRAMES, SUB-FRAMES AND CONNECTIONS

It is widely recognised that the connections are likely to affect strongly the overall structural response of a frame [4].

Inversely it has also been demonstrated [5] that the frame behaviour may influence the mechanical properties of the connections.

As a matter of fact, statically undeterminate structural systems experience redistributions of internal forces when loaded, so resulting in a non proportional evolution of the moments, shear and normal forces carried over by the connections. This situation leads to evolutive stress interactions and loading situations which are likely to alter the connection properties.

As a direct conclusion, the testing of isolated connections should therefore be avoided and only tests on full frames should be performed. But tests on whole frames are quite expensive to perform and require specific testing facilities; so, in most of the cases, connections are tested in isolation or as part of a sub-frame.

To minimize the discrepancy between the actual response of the connection in the frame and that registered during the test, the testing arrangement has to be elaborated so to ensure to the tested connection a similar environment than in the actual frame [6].

Many tests performed in the past and still nowadays do not fullfil this basic requirement. Either they have to be disregarded with purpose when developing models or they are incorrectly used to validate design models. In both cases the initial goal is not reached. The use of these test results for direct inclusion as data in a frame analysis software has also to be prevented. There are however situations where these tests can be used for validation of design models but this requires sophisticated models - usually not available to designers - able to take explicitely into consideration loading and "environment" parameters particular to the studied connection. In any case, the introduction of such tests in databases constitute a risk of misuse.

These conclusions have however to be tempered a bit. Various studies have shown that the sensitivity of the frame response to variations in connection properties is rather limited. Realistic environment conditions (loading, testing arrangement, boundary conditions) are therefore sufficient to prevent significant errors and mistakes in validating design models though comparisons with test results. Examples of such realistic testing arrangements are given here below.

In connections between I or H sections, shear deformation of the column web panel may occur; this leads to a S deformation of the column as shown in figure 4. Shear deformation of the column web panel is expected to be more pronounced in outer joints - where a single beam is connected to the column - than in inner joints (see figure 1). In laboratory, it shall therefore be distinguished between tee-joint configurations (figure 2.a), which are representative of outer joints in a real framework and balanced or slightly unbalanced cruciform joints which correspond to inner joints (figure 2.b).

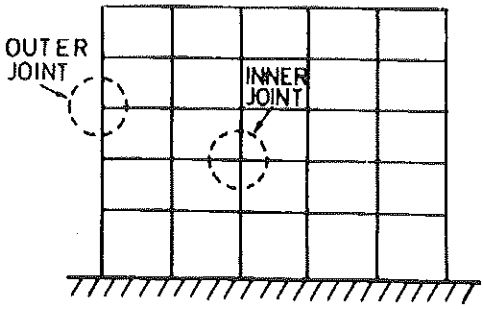

Figure 1 - Joints in a real framework

a. Tee joint

b. Cruciform joint

Figure 2 - Different testing configurations

Because the attention focuses on both strength and deformability, there are many governing parameters of several natures to be combined; therefore only tests on full-scale specimens are conceivable, because the sole likely to give accurate and realistic information regarding the behaviour of joints in real structures.

The usual test specimens are subassemblages as those presented in figure 2. The height of the column is chosen so that it represents roughly the height of one storey. The beam is connected at mid-eight of the column so that the ends of the latter may be considered as points of contraflexure at mid-storey in the columns of a sway frame subject to horizontal loads [6]. For sake of testing, it is thus sufficient to apply externally axial loads at the ends of the column. Bending in the column as a result of the loading of the beam(s) will be produced by the horizontal support reactions at the ends of the column.

What about the length of the beam(s) in tee- or cruciform joint specimens ? It is determined so to allow for bending-to-shear ratios in the connection similar to those encountered in practice (see figure 3). In this respect, it is while mentioning that some tests reported in the literature do not care at all for such conditions, which should however be considered as a requisite. Bending in the beam is produced by the load(s) applied at the end of the cantilever(s).

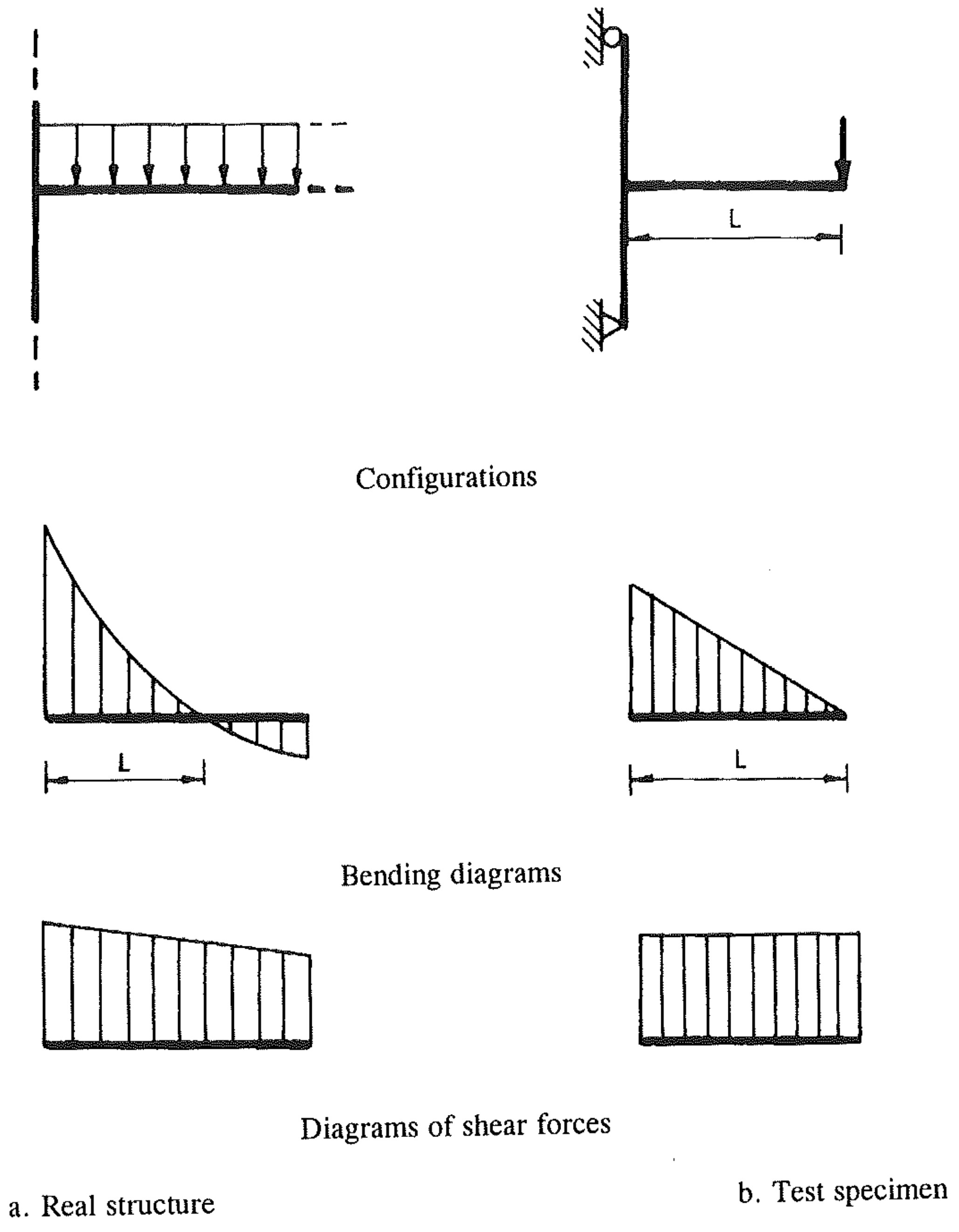

Figure 3 - Definition of the beam length in a test specimen.

EXPERIMENTS ON COMPONENTS

Most of the modern design models for connections are based on the so-called component method, as for instance in the new Eurocodes.

The component method may be presented as the application of the well-known finite element method to the calculation of structural connections.

A connection is generally considered as a whole and is studied accordingly; the originality of the component method is to consider any connection as a set of "individual basic components". In the particular case of figure 4 (extended end plate connection subject to bending), the relevant components are the following:

- compression zone:
  - column web in compression ;
  - beam flange in compression ;

- tension zone:
  - column web in tension ;
  - column flange in bending ;
  - bolts in tension ;
  - end plate in bending ;
  - beam web in tension ;

- in shear zone :
  - column web panel in shear.

Each of these basic components possesses its own level of strength and stiffness in tension, compression or shear. The coexistence of several components within the same connection element - for instance, the column web which is simultaneously subjected to compression (or tension) and shear - can obviously lead to stress interactions that are likely to decrease the strength and the stiffness of each individual basic component; this interaction affects the shape of the deformability curve of the related components but does not call the principles of the component method in question again.

The application of the component method requires the following steps:

a) listing of the "activated" components for the studied connection ;
b) evaluation of the stiffness and/or strength characteristics of each individual basic components ;
c) "assembling" of the components in view of the evaluation of the stiffness and/or strength characteristics of the whole connection.

As specified here above, the parallelism with the finite element method is obvious. To "component" and "connection" may here be substituted the words "finite element" and "structure".

The "assembling" is based on a distribution of the internal forces within the joint. As a matter of fact, the external loads applied to the joint distribute, at each loading step, between the individual components according to the instantaneous stiffness and resistance of each component.

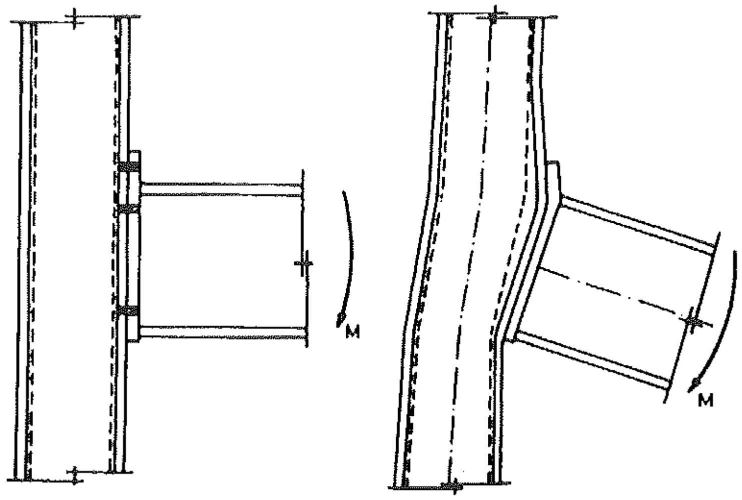

Figure 4 - Joint in bending with extended end plate

The application of the component method requires the evaluation of the stiffness and resistance properties of the basic components though appropriate analytical models, the validation of which requires experimental tests on individual components.

When performing these tests, the fact that connections may interact in the actual connections has not to be disregarded to be sure that the component response got from the test reflects the actual response in the real connections.

TEST MEASUREMENTS

The tests have to be instrumented so to allow the determination of the deformation of the connection as a whole or of the constitutive components at each load level. For this purpose, electronics transducers are used. The applied load as well as the support reactions are also measured by means of load cells.

The main properties characterizing the connections (moment, resistance, rotational stiffness,...) are obtained by combining different measurements.

It is recommended to perform "redundant" measurements which shall allow for computing a specified connection property by at least two different manners. Doing so warrants to get results even when one transducer is misfunctioning or when something wrong occurs during the test. The "direct" measure is of course preferable and the most thrustable but the searched information must also be deductable from "undirect" measurements, when necessary. A peculiar attention must be paid to avoid second-order effects which could arise during the tests and could affect appreciably the measured values; possibly they must be properly accounted for.

These precautions allow to obtain good and reliable measurements but bring no help in answering the following question: "What to measure, and where ?". Moments and related rotations are measured since years and years by experimentators through the world, but the study of the resulting test reports produced in the past lead the reader to the conclusion that few experimentators clearly indicate where and how the moments and rotations are measured. Hundreds of tests performed in the past are of no help today, just because the definition of the computed connection properties based on the test measurements are not specified.

As a conclusion, it should be recommended to any person involved in experimentation on connections to indicate in the test reports what are the measurements made during the tests, where the measurements are made and how the measurements have been combined after the testing to evaluate the main stiffness and resistance properties of the connections. Finally, all the individual measurements and all these combinations made after the test should be listed in the report. This is the only way to allow people interested in the tests to understand exactly what are the reported values and to use them in an appropriate way when designing a frame (designer) or when developing or validating design models (researcher). This is also necessary in view of the inclusion of the test in a database as SERICON.

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