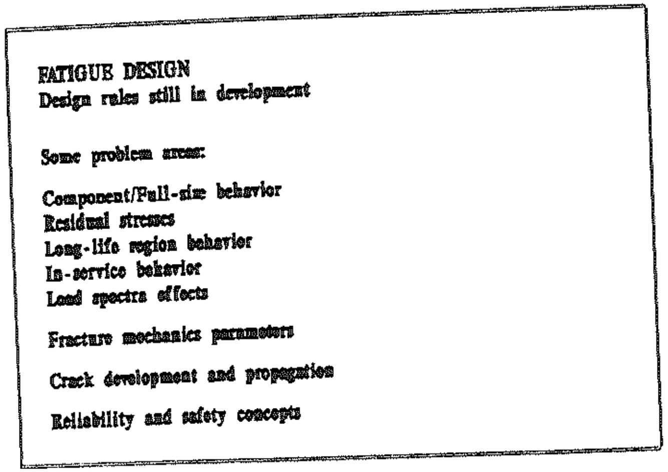


FATIGUE DESIGN
Design rules still in development

Some problem areas:

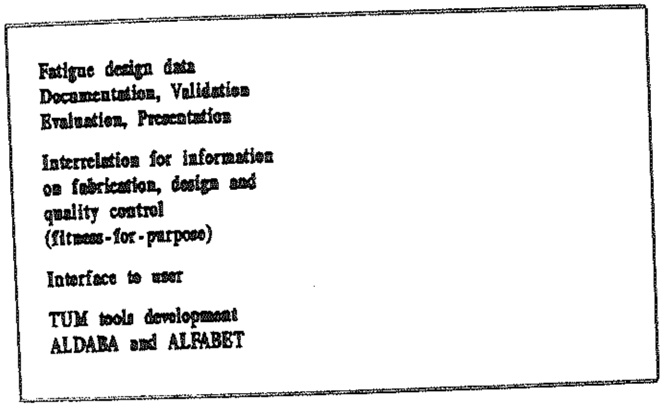
Component/Full-size behavior
Residual stresses
Long-life region behavior
In-service behavior
Load spectra effects

Fracture mechanics parameters

Crack development and propagation

Reliability and safety concepts

Fig. 8: Fatigue Design - Areas of Development



Fatigue design data
Documentation, Validation
Evaluation, Presentation

Interrelation for information
on fabrication, design and
quality control
(fitness-for-purpose)

Interface to user

TUM tools development
ALDABA and ALFABET

Fig. 9: Recording and Dissemination of Information

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6 INVESTIGATION BY TESTING OF THE STRUCTURAL RESPONSE OF SEMI-RIGID JOINTS

J.P. JASPART and R. MARQUOI
Département M.S.M., Civil Engineering Institute, University of
Liege, Belgium

SUMMARY

During the last decade semi-rigid joints has focused the attention of several European researchers, regarding not only their actual behaviour but also on how and to which extent they alter the stability of frameworks. That is testified by the number of papers, dealing with this subject, presented at this Napoli Workshop. Extensive investigations have been and are still carried out in Liège on these topics either experimentally, or theoretically and numerically; bare steel- and composite joints are of concern. Accounting for the scope of the Workshop, present paper is restricted to several aspects of the testing.

1 INTRODUCTION

The knowledge of the actual behaviour of beam-to-column joints is of paramount importance; it is indeed likely to influence very much both idealization and discretization of the structure before performing the structural analysis, i.e. determining the stress resultants.

In the past, the current methods of structural analysis allowed only either for rigid joints or for pin-ended connections; the detailing of the joints was made in view to comply as much as possible with the corresponding assumptions.

A rigid beam-to-column joint should not allow for any relative rotation between the axis of the respective intersecting members; as a consequence, any external bending moment applied on this joint distributes amongst the connected members according to the member flexural stiffnesses. In contrast, a beam that is pin-ended to columns should freely rotate at the ends without transferring any bending to the column; this rotation at the ends is depending on the beam loading only.

Such extreme behaviours are respectively represented, in a bending - relative rotation curve, by the axis of ordinates for a rigid joint and by the axis of abscissae for a pin-ended beam-to-column connection.

Of course no joint is never either fully rigid or actually pinned. More especially, a presumed rigid joint always allows fo a relative rotation, even when the column web panel is transversely and diagonally stiffened and the connection of the beam made with stiff end-plate and preloaded bolts; however the rotation of such a joint remains usually so

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small that the assumption of a rigid joint is quite acceptable. Presumed pin-ended connections, for their own, are always somewhat restrained because the actual connecting devices are never proper hinges; the corresponding constructive detailing is identified to hinges for sake of conservatism. Let us mention in addition that it is distinguished between full strength and partial strength joints; in the first case the joint is able to transmit the full resistance of the connected members, while in the second one, the connection is weaker than these members.

Rigourously speaking, any joint is ever neither fully rigid, nor pinned; therefore it should be termed as semi-rigid (fig. 1).

Modern steel construction aims at not only material savings but more especially at cost savings. In this respect, the detailing of the joints is simplified : the number of stiffeners in the joint is reduced, as well as the length of fillet welds; that results in an appreciable decrease in labour cost and consequently favours the global economy of the project. At the structural viewpoint, that leads to beam-to-column joints which are much more simple to execute but exhibit a fully non-linear behaviour and therefore a M-ϕ curve, which is sometimes very far from the characteristic curve of a rigid joint.

Such a semi-rigid and partial strength behaviour of the joints shall affect both the strength and the stability of steel frames. The corresponding structural response shall be non-linear; the non-linearity of the joint behaviour superimposes to possible material and geometric non-linearities. Several computer programmes allowing for those kinds of non-linearity are yet available. Most of them substitute each semi-rigid joint either by a notional linear rotational spring (constant stiffness whatever the moment amplitude) or better by a notional non-linear rotational spring; sometimes a piecewise linear characteristic curve is substituted for the actual non-linear one (fig. 1). The M-ϕ characteristic curve of such a spring represents the global response of the joint. Actually there are several components of the joint deformability, whose respective contributions are governed by many parameters. The relative amounts of these contributions are depending on the loading of the joint; therefore the response of a joint within a structure may be somewhat different from that of a joint belonging to a subassemblage tested in specified laboratory conditions. As a consequence, tests must be carried out so that all the sources of deformability be measured separately; the corresponding results are aimed at being used to calibrate physical models which, theoretically based, should allow the prediction of all the deformability contributions in a wide range of variation of the governing parameters.

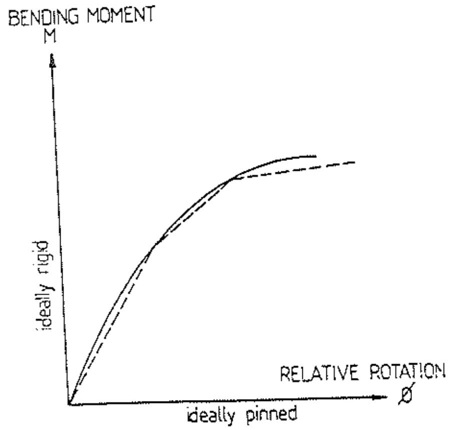


Figure 1

Present paper is dealing with in-plane semi-rigid joints under gravity static loading only.

2 SOURCES OF JOINT DEFORMABILITY

The sources of deformability are being clearly identified first. For the reasoning, let us assume an in-plane strong axis beam-to-column joint, for which the end cross-section of the beam is connected, whatever the manner, to one flange of the column so that any loading experienced by the beam in the plane of the framework induces bending about the strong axis of the column cross-sectional area (fig. 2.a).

A *joint* is the whole region concerned by the assemblage of the beam(s) with the column. It is composed by the very end portion of the beam(s), the facing adjacent portion of the column, as well as by all the connecting accessories (end plate, cleats, bolts, welds,...) required by a specified type of connection. The deformability of a strong axis beam-to-column joint consists mainly in two parts, which are respectively fed by several contributions :

a) The deformability of the *connection area* associated to the following phenomena :
  - Deformation of the connection elements : end plate or cleats, bolts, rivets, welds,...
  - Slip and/or hole clearance ;
  - Deformation of the column web, across its depth, in the so-called tensile and compression zones, i.e. in the regions where the forces carried over by the beam(s) have to diffuse into the column web (this effect, termed "trapezoïdal effect", is the result of the respective lengthening and shortening of the column web depth).

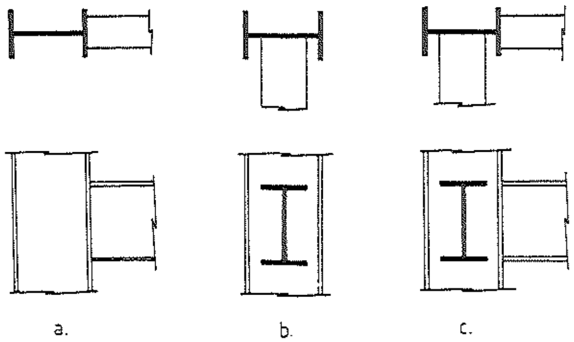


Figure 2

b) The shear deformation of the *column web panel*, which is subject to a complex shear stress distribution in the region of the joint.

In a weak axis beam-to-column joint (fig. 2.b), the end cross-section of the beam(s) would directly be connected, whatever the manner, to the web of the column; any transverse load experienced by the beam in the plane of the framework should result in bending about the weak axis of the column. For such a joint the aforementioned "trapezoïdal effect" vanishes and the second source of deformability results mainly from the out-of-plane deflection of the column web when experiencing the bending moment transmitted by the beam(s).

For a 3 D-joint (fig. 2.c), beams are connected at about the same location to a single column, respectively onto the web and one (or two) flange(s) of this column, so that the deformability results roughly from the combination of the sources identified above, respectively to both axis, with account taken of the possible interactions.

Let us reason on a strong axis beam-to-column joints. The contribution θ of the deformability of the connection area to the joint relative rotation ϕ is defined by the difference between rotations θ_b and θ_c (fig. 3.b). That of the shear deformation of the column web is represented by the difference between θ_c and θ_f, where θ_f is the flexural rotation of the column (fig. 3.b).

Regarding the shear force in the column web panel, it shall be stressed that it results from : i) the combined action of equal but opposite forces F_b in the beam flanges, the resultant of which is statically equivalent to the bending moment in the beam, and ii) the shear force resulting from the moment distribution in the column.

Because both sources of deformability are dealing with the response of two different zones of the beam-to-column joint, their contributions shall be assessed with reference made to their respective appropriate loadings. As these latter are not identical, it must therefore be accounted for both deformability sources separately and laboratory tests have to be instrumented in such a way that measurements of the deformability components be possible.

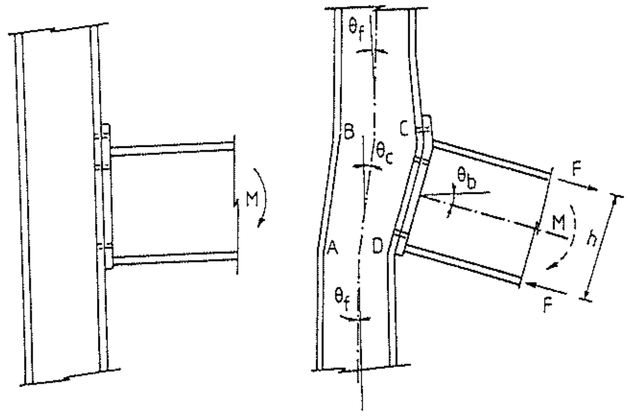


Figure 3

Though tests have been conducted in Liège on all above mentioned kinds of joints, only strong axis beam-to-column joints are of concern in the following, except where it is stated otherwise. The scope is restricted to hot-rolled sections only.

3 TEST SPECIMENS AND TESTING ARRANGEMENTS

Because only the response of in-plane semi-rigid joints is of concern, the experiments are of course conducted not on whole structures but on *structural subassemblages* composed of portion(s) of beam connected to a portion of column. These subassemblages must be designed so that to allow for realistic types of loading, while having sizes which prevent external load introduction effects from alterring the response of the joint itself.

Shear deformation of the column web panel is expected to be more pronounced in tee-joints, where a single beam is connected to the column (fig. 4.a). In contrast, the "trapezoïdal effect" exhibits as well in tee-joints as in cruciform joints, where two beams are connected to the column at the same level and are both similarly loaded (fig. 4.b). Therefore it shall be distinguished between tee-joints, which are representative of outer joints in a real framework, and cruciform joints which correspond to inner joints of this structure (fig. 5).

Because the attention is focused on both strength and deformability ability, there are many governing parameters of several natures; 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.

As already mentioned above, the test specimens are subassemblages. The height of the column is chosen so that it represents roughly the depth of one storey. The beam is connected at mid-height of the column, so that the ends of the latter may be considered as points of contraflexure in the columns of a sway frame subject to horizontal loads.

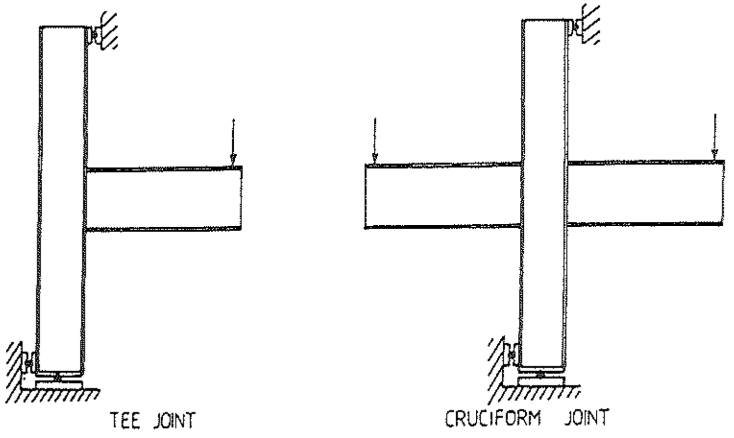


Figure 4

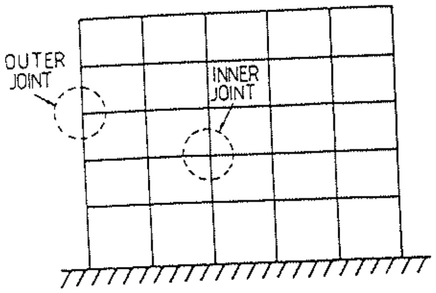


Figure 5

For sake of testing, it is thus sufficient to apply axial load 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 in view to allow for bending-to-shear ratios in the connection similar to those encountered in practice. In this respect, it is while mentioning that some tests reported in the literature do not care at all for such condition, which should however be considered as a requisite. Bending in the beam is produced by point load(s) applied at the end of the cantilever(s).

When semi-rigid composite joints, the steel column is connected with the composite beam(s), composed of a hot-rolled section associated to a reinforced concrete slab, by means of shear connectors. Slab has a spatial structural behaviour. Because only in-plane tests are carried out the composite test specimens must be carefully designed in order to get an appropriate composite action. In this respect, the distribution of direct bending stresses across the slab width must be quasi uniform in the joint cross-section. Because the bending moment is produced by point load(s) at the end of the cantilever beam(s), the width of the slab in the test specimens cannot be smaller than the regular effective width, which is aimed to allow for the aforementioned required stress distribution. This condition must also be adopted as a prerequisite; it is checked by means of measurements, during the tests, of the direct stresses in the steel reinforcements in several cross-sections, and especially in the joint cross-section.

The test specimen is inserted in a steel testing rig, that is fixed on the 1.5 m thick concrete testing floor of the laboratory. This rig is aimed at providing the reactions required by the loads to be applied to the test specimen.

The ends of the column are supported by devices which are able to support vertical and horizontal reactions while providing no moment restraint; they can thus be considered as ideally hinged.

Guide-plates are located all along both the beam(s) and the column in view to prevent from any spatial behaviour and out-of-plane displacement of the subassemblage whose in-plane behaviour is investigated only.

Load is applied at the end of the cantilever(s) and possibly in the column by means of hydraulic jacks fitted with load cells. The load is increased up to the joint collapse or to the maximum deflection of the cantilever ends according to what is first reached. Unloading are carried out during the tests in view to compare the instantaneous stiffness with the initial one.

4 INSTRUMENTATION AND MEASUREMENTS

The tests are instrumented so that the measurements allow for determining the amplitude of all the components of the joint deformability at any level of the loading. It is useful to perform measurements of horizontal and vertical displacements as well as of rotations in appropriate sections; for this purposes, electronic transducers are used. The applied load as well as the support reactions are also measured by means of load cells.

As it is required to identify and measure separately all the components of the joint deformability, it is of paramount importance that the measurements be scheduled accordingly. In other words, it is necessary to perform "redundant" measurements which shall allow for computing a specified rotation by at least two different manners. Doing so warrants to get results even when one transducer is misfunctioning or when something wrong is likely to occur during the test. The "direct" measure is of course preferable and the most thrustable but the searched information must also be deducable from "undirect" measures, 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.

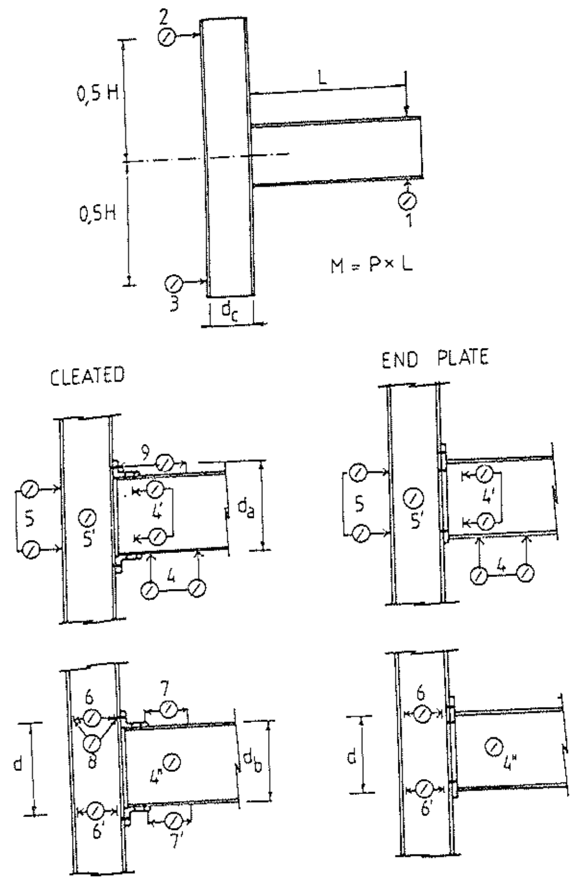
Last the testing frame, which is anchored on the testing floor of the laboratory and is aimed at resisting the applied load and the support reactions, cannot be undeformable, whatever its rigidity. Therefore, because rather small quantities are to be measured, one must avoid to use this rig as support for the measurement devices. Accessories independent of the testing rig are therefore clamped on the testing slab whose rigidity can be considered as infinite. Following measurements are made for tee-joints (Table 1):

a) vertical and horizontal displacements at the end(s) of the beam and the column ;
b) rotations of the beam and of the column ;
c) rotation associated to the load introduction deformability of column web ;
d) rotation due to the slip at the junction cleat-beam flange ;
e) proper deformation of the upper flange cleat ;
f) proper deformation of the column flange in the tension zone of the joint.

The last three measurements are only performed for flange cleated connections.

In view to compute the rotation of the beam and of the column, six measurements were made (Table 1). The transducers (5) on the column flange are located symmetrically to the axis of the beam in the plane of the column web and on the outer flange of this column. Their spacing is as large as allowed by the beam depth. Transducers (4′) are pointing to

Table 1
INSTRUMENTATION



ROTATIONS

MAIN COMPONENTS

— CONNECTION

$\theta = \theta_b - \theta_c$ (fig 3b) θ_b by ④ ④' or ④"
θ_c by ⑤ or ⑤'

— SHEAR OF COLUMN WEB PANEL

$\gamma = \theta_c - \theta_f$ (fig 3b) θ_f theoretically evaluated
or
$\gamma = \emptyset - \theta$

— JOINT

$\emptyset = \theta + \gamma$ or $\emptyset = F[(1),(2) \text{ and } (3)]$

COMPONENTS OF CONNECTION DEFORMABILITY

— LOAD INTRODUCTION

$\theta_{li} = [⑥ - ⑥']/d$

— SLIP

$\theta_s = [⑦ - ⑦']/d_b$

— CLEAT/END PLATE & COLUMN FLANGE

$\theta_d = \theta - \theta_s - \theta_{li}$

— COLUMN FLANGE

$\theta_{cf} = [⑧ - ⑥]/d$

— CLEAT incl. BOLT ELONGATION

$\theta_a = \theta_d - \theta_{cf}$

$\theta_a = [⑨ - ⑦]/d_a$

their small stitches welded transversely into the web; they are also located symmetrically to the beam axis. Transducers (4) are located at the lower flange of the beam as near as possible to the connection cross-section.

The measurements of the rotation resulting from the slip at the interface between the flange cleat and the beam flange is made by measuring the relative displacement between two points located at a so small spacing as possible, respectively on the cleat and on the flange on both upper and lower flanges respectively (Transducers 7 and 7' in Table 1).

Direct measurements of the deformation of the column web in the compression and tension zone are made in view to get the deformation curve associated to the "trapezoïdal effect" in the column web panel (Transducers 6 and 6' in Table 1).

The computation of the rotation due deformation of the column flange results from the measurement of the relation displacement (8) between two points located respectively on one of the bolts connecting the upper cleat to the column and the column web (Table 1).

The rotation due to the deformation of the cleats (including the bolt elongation) is deduced from measurements of the relative displacements between the two points located at a so small spacing as possible respectively on one of the bolts connecting the upper cleat to the column and on the upper beam flange, (Transducers 9 in Table 1).

When cruciform joints, the deflections and the rotations are determined accordingly for both beam-to-column connections.

Composite connections require in addition the measurement of the slip between the concrete slab and the adjacent steel flange onto which the slab is connected by studs.

Strain measurements are aimed at investigating the stress distribution in the beam cross-section. For bare steel beam-to-column joints, only some tests have been fully instrumentd in this respect; it has soon appeared that strain measurement in both flanges of the beam in two cross-sections is quite sufficient. For composite joints, strain measurements not only in both flanges of the steel beam but also in the reinforcements have been made in several cross-sections in view to explore the stress distribution, more especially in the concrete slab because of the shear lag effect. As soon as it has been demonstrated that a uniform direct stress distribution in the slab in the cross-section corresponding to the connection was reached, the following tests have been conducted with a less important instrumentation.

The measurement of the beam rotation (fig. 3) has revealed to be rather dubious in most of the tests performed. That is the consequence of: i) the out-of-plane deformation of the beam web during the joint loading as a result of the dissymetry of some connection types or, ii) the distance between the real connection cross-section and the section where the rotation measurement is performed. However that does not at all prevent from determining the rotation of the beam because of the redundancy of the measurements performed. It has been anyway concluded that a direct measure by means of potentiometrical rotating transducers is far preferable and such devices have been purchased.

One must also stress the fact that the determination of the rotations may be questionable when beam and/or column behave inelastically. That is especially important when computing rotation θ_f.

5 DATA ACQUISITION

Measurements have been recorded during tests by means of a Hewlett-Packard data logger, which is able to measure up to 200 different parameters (transducers, strain gauges,...) at a time.
This data logger is automatically commended by a software running on a PC computer. This software - SCANPACK - was developed in the Liège laboratory ; it is especially useful for tests on structures and allows to follow, in real time on the screen, the evolution of any reference measurement versus the applied load. All the measurements are stored in

iew to further analysis of the results. This package stores in addition ll the information regarding the test conditions (connections of easuring devices, calibration factors,...); that is especially useful for repetitive tests.

6 EXPERIMENTAL CHARACTERISTIC CURVES

Because of the appropriate instrumentation, the following characteristic curves, associated to the different components of the joint deformability have been recorded :

a) the joint relative rotation curve ;
b) the connection relative rotation curve ;
c) the column web panel rotation curve ;
d) the moment-deflection curve.

For what concerns especially the deformability of the strong axis connection, it is composed by the addition of the following curves :

a) the load introduction rotation curve ;
b) the connection slip rotation curve (cleated connections) ;
c) the cleat deformability rotation curve (cleated connections) ;
d) the column flange rotation curve (cleated connections) ;
e) the column flange and end plate deformability rotation curves (end plate connections).

Figure 6 presents the different curves recorded for a specified test specimen.

Readers interested in knowing more about the test results are begged to refer to publications and reports listed in the following section.

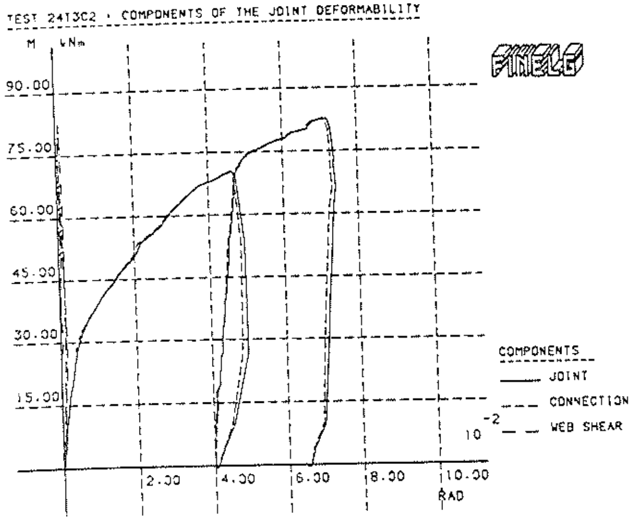


Figure 6.a.

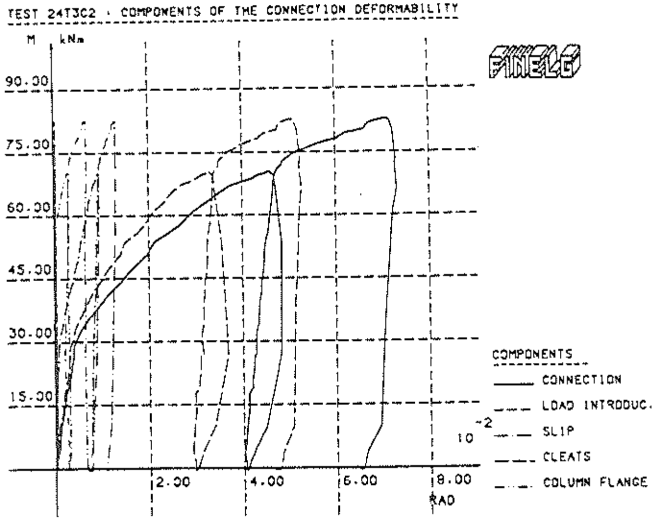


Figure 6.b.

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