Definitions of Resistance and Deformation Capacity for Non-Sway Steel and Composite Structures

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Resistance, stiffness and deformation capacity are three characteristics describing the behaviour of (statically loaded) structures. The stiffness relates mostly to the serviceability of the structure. The resistance and deformation capacity relate to the safety of the structure.
Nowadays, the safety of structures is checked explicitly with help of probabilistic methods. Studies using these methods focus very much on the resistance (strength and stability) of structures. Normally, the objective of such studies is the probabilistic assessment of partial safety factors for design standards.
The item discussed in this paper is the definition of deformation capacity from the viewpoint of structural reliability. This definition cannot be seen independently from the definition of resistance.
This paper presents the results of a deterministic parametric study on the definitions of resistance and deformation capacity. The structural system under consideration is a steel-concrete beam with two joints connecting the beam to a rigid core.
The work presented in this paper should be seen as a step towards an understanding of the reliability of structures in relation to deformation capacity. The next step of this study will be a parameter study based on a reliability approach[1)]. The objective of this work is to assess influencing parameters of the effect of deformation capacity on the reliability of structures. This study is carried out at Eindhoven University of Technology.

Key words: **Steel, Composite, Resistance, Deformation Capacity, Definition, Reliability**

[1)] Due to the untimely decease of the first author, the project has (temporarily) been stopped. Also see the 'In memoriam Martin Steenhuis'.

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Notations

l	span of a composite beam;
l'	span of a composite beam in a three point load test;
$l_{s,} l_h$	half of the total beam length where sagging or hogging moments occur respectively;
q	load on a composite beam;
q_{test}, q_{model}	maximum load on a composite beam in a test and in a model respectively;
EI_s, EI_h	elastic stiffness of a beam subjected to sagging or hogging moments respectively;
F	load on a beam in a three-point load test;
F_p	plastic load on a beam in a three-point load test;
M_b	moment in a beam, derived from a test, $M_b = {}^1/_4\, F\, l'$;
$M_{b.el.exp}$	moment in a beam, derived from a test, at the end of the elastic branch;
$M_{b.pl.exp}$	moment in a beam, derived from a test, at the start of plastic behaviour;
$M_{b.post.exp}$	moment in a beam, derived from a test at the end of the post limit branch;
$M_{b.u.exp}$	ultimate moment in a beam, derived from a test;
M_j	moment in a joint;
$M_{j.Rd}$	design moment resistance of a joint according to Eurocode 3 or 4;
$M_{j.Rmod}$	moment resistance of a joint on model level based on a test;
$M_{j.el.exp}$	moment in a joint, derived from a test, at the end of the elastic branch;
$M_{j.pl.exp}$	moment in a joint, derived from a test, at the start of plastic behaviour;
$M_{j.post.exp}$	moment in a joint, derived from a test, at the end of the post limit branch;
$M_{j.u.exp}$	ultimate moment in a joint, derived from a test;
R_j, R_b	dimensionless definition of rotation capacity for joint and beam respectively;
$S_{Eb.ini.exp}$	initial stiffness of a beam in a three-point load test;
$S_{Eb.post.exp}$	post limit stiffness of a beam in a three point load test;
$S_{j.desc.exp}$	descending stiffness of a joint;
$S_{j.ini}$	initial stiffness of a joint according to Eurocode 3 or 4;
$S_{j.ini.exp}$	initial stiffness of a joint, derived from a test;
$S_{j.ini.mod}$	initial stiffness of a joint, on a model level $S_{j.ini.mod} = S_{j.ini.exp}$;
$S_{j.load\text{-}unload.exp}$	loading/unloading stiffness of a joint, derived from a test;
$S_{j.post.exp}$	post limit stiffness of a joint, derived from a test;
δ_{mid}	deflection at mid span;
δ_{lim}	limit deflection at mid span, $\delta_{lim} = 1/50$ times the beam span;
ϕ_{Cd}	design rotation capacity of a joint according to Eurocode 3 or 4;
ϕ_{Cmod}	rotation capacity of a joint on model level based on a test;
ϕ_{Xd}	rotation at the start of the plastic plateau of a joint according to Eurocode 3 or 4;
ϕ_{Eb}	rotation of a beam end;
$\phi_{Eb.exp}$	elastic rotation of a beam end under plastic load in a test;
ϕ_b, ϕ_j	rotations in an equivalent plastic spring at mid span of a beam or in a joint respectively;

$\phi_{j.cap.exp}$	rotation capacity of a joint derived from a test;
$\phi_{j.pl.exp}$	rotation of a joint, derived from a test, at the start of plastic behaviour;
$\phi_{j.post.exp}$	rotation of a joint, derived from a test, at the end of the post limit branch;
$\phi_{j.tot.exp}$	total rotation of a joint, derived from a test, at the moment level $M_{j.pl.exp}$;
$\phi_{j.u.exp}$	rotation of a joint at the ultimate moment, derived from a test;
$\eta_{b,} \eta_{j}$	ratio between initial stiffness and secant stiffness at the start of the post limit branch of a beam and joint respectively, derived from a test.

1 Introduction

The safety levels obtained by application of modern design standards for predominantly statically loaded building structures are nowadays determined using reliability studies. Vrouwenvelder and Siemes [1] describe a typical example of such a study, which concerns the probabilistic calibration of the partial safety factors in the Netherlands building codes. The underlying conception of this calibration process is that the level of safety embodied in the existing code from 1972 as a whole is acceptable and that the proposed code from 1990 should be calibrated against it. Since the code of 1990 is based on a partial safety factor approach, the values of the partial safety factors are chosen such that with the new code the reliability level of the old code is met (the reliability index is 3,8).

The basic procedure followed in the calibration process was as follows:

1. structural beams, columns and joints are designed according to the existing code;
2. mathematical failure models to be included in the proposed code are selected;
3. stochastic models for resistance and loads to be included in the proposed code are selected;
4. reliability analyses are carried out on the elements designed in step 1. These yield into a probability of failure of structures designed according to the existing code but analysed based on the proposed code;
5. proposals for partial safety factors are made such that the reliability level of the proposed code is equal to the one of the existing code on the average.

The calibration process is carried out on a structural element level. In other words beams, columns and joints are investigated. The following limit states are taken into consideration: resistance, deflections and crack width. The elements concerned are made of steel, concrete or timber. In reality, the safety of a statically loaded structures is not only dependent on the resistance of the structural elements, but also on the structural system as a whole, for which deformation capacity plays an important role. Deformation capacity is required for two reasons.

1. Structures are subjected to not foreseen or unexpected loads or settlements, which cause different force distributions in the structure than those, anticipated during design. These forces possibly lead to local deformations in the structure for which deformation capacity is required.
2. In case of plastic design, the structure should be able to undergo the foreseen plastic deformations for which deformation capacity is required.

The current reliability studies do not explicitly take into account deformation capacity as a limit state condition, although this capacity has an influence on the system reliability. At Eindhoven University of Technology, a research program is carried out on the relation between deformation capacity and the structural reliability.

This paper presents a part of this research activity. In a previous paper [2], a method has been developed how to determine partial safety factors for deformation capacity. This method utilises reliability methods assuming elastic-rigid plastic behaviour of the structure and its elements. The real safety of the structure may however differ from the calculated safety of the structure based on elastic-rigid plastic characteristics. In literature, different approaches are given for these elastic-rigid plastic characteristics (strength, stiffness and deformation capacity) of structural elements (joints, members) obtained from their real behaviour.

In this paper, the "real" resistance of structures is compared to the calculated resistance based on elastic-rigid plastic behaviour. This comparison is made for the various approaches given in literature to derive the elastic-rigid plastic characteristics determined by strength, stiffness and deformation capacity. The focus is on behaviour of steel-concrete composite members and joints subjected to bending moments.

The resistance of structures is given on a so-called *test level*. The elastic-rigid plastic characteristics are given on a so-called *model level*. In paragraph 2, definitions are given of these test and *model level*. To be complete, also a description is given of the *design level*. Paragraph 3 gives an overview of the approaches given in literature to derive the resistance, stiffness and deformation capacity of steel and composite joints from tests. The approaches adopted for steel and composite members are described in paragraph 4. In paragraph 5, the set-up of a parameter study is given. With this parameter study, the ratio of the resistance of a composite beam system on a *test level* and on a *model level* is investigated. This is done according to the various approaches given in literature to derive the elastic-plastic characteristics from tests. The objective is to gain knowledge about this ratio, the influencing parameters and the accuracy of the approaches to derive values for resistance, stiffness and deformation capacity. In paragraph 6 conclusions and recommendations for further research are given.

2 Test, design and model level

Concerning structural elements in bending, Kuhlmann et al. [3] defined the *test level* as follows. At the *test level*, the following features of structural element behaviour are taken into account (the symbols refer to a steel or composite beam-to-column joint only):

- initial (elastic) stiffness $S_{j.ini.exp}$;
- post limit stiffness $S_{j.post.exp}$;
- descending stiffness $S_{j.desc.exp}$;
- loading/unloading stiffness $S_{j.load\text{-}unload.exp}$;

- deformation (rotation) capacity $\phi_{j.cap.exp}$;
- peak moment, $M_{j.u.exp}$.

Fig. 1 shows these features in a typical load-deformation diagram of a steel or composite beam-to-column joint. In this figure, the deformation capacity $\phi_{j.cap.exp}$ is simply taken as the rotation occurring at fracture of the joint. In literature, the definition of deformation capacity is however still under discussion.

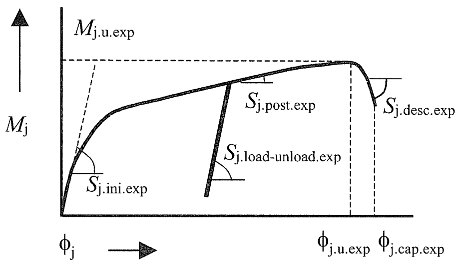

Fig. 1: Test of a beam to column joint.

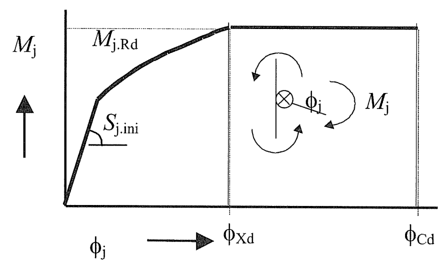

Fig. 2: $M_{j.Rd,}$ $S_{j.ini,}$ ϕ_{Xd} and ϕ_{Cd} according to Eurocode 3 and 4.

Kuhlmann et al. [3] also defined the *model level*. At this *model level*, the post limit stiffness and the descending branch are simply replaced by a plastic plateau. The loading/unloading stiffness is not taken into consideration. Hence, there are three mechanical properties to describe the moment rotation characteristic of a structural element in bending: resistance, stiffness and deformation (rotation) capacity. There are two ways of calculating characteristics on the *model level*, which ideally lead to the same results.

1. Values can be derived directly from the *test level* based on a deterministic procedure. This is the focus of this paper.
2. Values can be derived based on a model, provided that its basic variables are based on measured or stochastic values. This approach is used in calibration studies, as described by Siemes and Vrouwenvelder [1], which focus on the relationship between the *design level* and the *model level*.

The *design level* has the same characteristics as the *model level*, but also partial safety factors are taken into consideration. The design level is used in standards like Eurocode 3 [4] and Eurocode 4 [5]. In these codes the definitions of the design moment resistance $M_{j.Rd}$, bending stiffness $S_{j.ini}$ and the design rotation capacity of a joint ϕ_{Cd} are given as represented in Fig. 2[1].

[1] Kuhlman, et al., [3] give other definitions for the design rotation capacity than Eurocode 3 and 4. There is however a direct relationship between these definitions of rotation capacity and the definitions given in Eurocode 3 and 4. Wich definitions should be used seems therefore a matter of taste and practicality. In this paper, the definitions of Eurocode 3 and 4 are adopted.

Table 1 summarises all views.

Table 1: Views on Structural Behaviour

Level	*Approach*	
Test	Test characteristics	
Model	1) Characteristics derived directly from tests according to a deterministic procedure	2) Characteristics based on model prediction with measured or stochastic basic variables
Design	Characteristics based on model prediction with characteristic basic variables and calibrated partial safety factors	

3 Derivation of steel and composite joint characteristics on the *model level*, approach 1

The question arises how to determine the moment resistance $M_{j.Rmod}$, the initial stiffness $S_{j.ini.mod}$ and the rotation ϕ_{Cmod} from a specific test result. Jaspart [6] gives an overview of approaches how to determine the moment resistance at *model level* $M_{j.Rmod}$ from a test. This overview is commented in [7]. In all approaches, the initial stiffness on the model level $S_{j.ini.mod}$ is simply taken as the initial stiffness at the test level $S_{j.ini.exp}$.
Fig. 3 shows a proposal by Jaspart how the design moment resistance $M_{j.Rmod}$ can be read from a test curve by drawing a line through the part of the test curve with post-limit stiffness $S_{j.post.exp}$. Where this line crosses the vertical axis of the M-ϕ curve, the level of $M_{j.Rmod}$ is defined. The deformation capacity ϕ_{Cmod} is taken at the intersection of the plastic plateau of the design curve with the descending branch of the test curve.
Alternatively, Zanon & Zandonini give a definition of $M_{j.Rmod}$ as illustrated in Fig. 4 [8]. In this case, $M_{j.Rmod}$, corresponds to the intersection of the initial stiffness $S_{j.ini.exp}$ and the strain hardening stiffness $S_{j.post.exp}$.
Crisinel & Kattner [9] use a similar definition as Jaspart to derive the rotation capacity from a test result. In this case, the moment level $M_{j.Rmod}$ is chosen as 0,9 times the ultimate resistance of the joint $M_{j.u.exp}$, see Fig. 5.
Weynand [10] suggested another possible definition. In this case, the initial stiffness of the joint is assessed in the M-ϕ curve, as being the elastic stiffness. Then, a secant stiffness is determined as the initial stiffness divided by a fixed factor. Where this secant stiffness intersects with the experimental curve, the level of the moment resistance $M_{j.Rmod}$ is defined. In agreement with the design model in Eurocode 3, Weynand proposes that the secant stiffness is taken equal to one third of the initial stiffness $S_{j.ini.exp}$, see Fig. 6. The deformation capacity ϕ_{Cmod} is taken at the moment level where $M_{j.u.exp}$ occurs.

It is also possible to combine the definition of the design strength of Weynand with the deformation capacity as used by Crisinel & Kattner. Generally, this will yield a larger deformation capacity in comparison with the approach of Weynand, see Fig. 7.

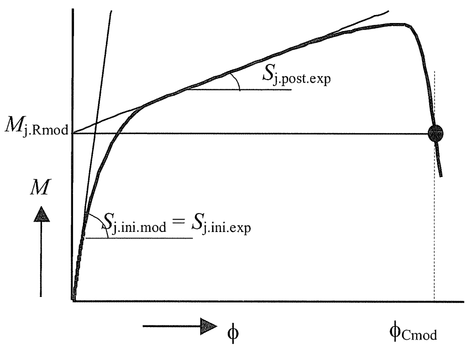

Fig. 3: $M_{j.Rmod}$, $S_{j.ini.mod}$ and ϕ_{Cmod} according to Jaspart [6].

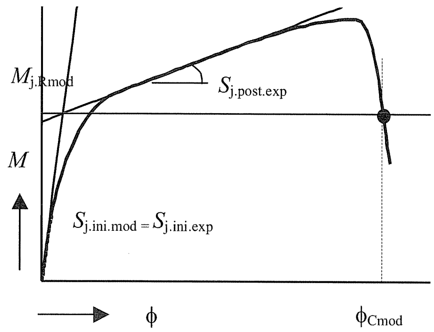

Fig. 4: M_{Rexp}, $S_{j.ini.mod}$ and ϕ_{Cmod} according to Zanon & Zandonini [8]

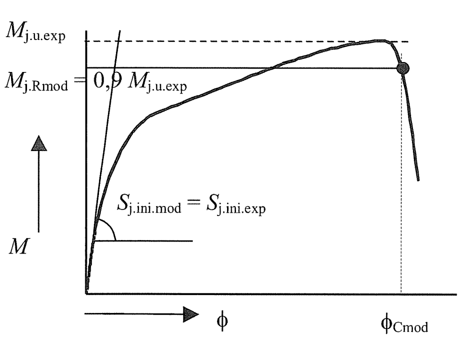

Fig. 5: $M_{j.Rmod}$, $S_{j.ini.mod}$ and ϕ_{Cmod} according to Crisinel & Kattner [9].

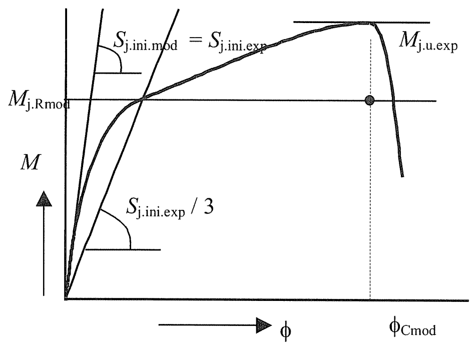

Fig. 6: $M_{j.Rmod}$, $S_{j.ini.mod}$ and ϕ_{Cmod} according to Weynand [10].

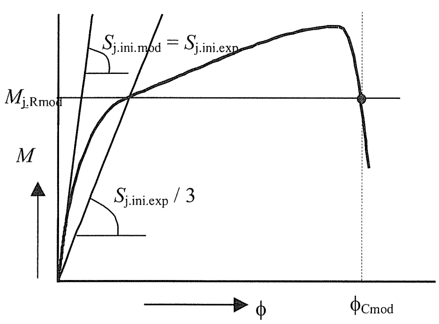

Fig. 7: $M_{j.Rmod,}$ $S_{j.ini.mod}$ and ϕ_{Cmod} according to Crisinel & Kattner [9] in combination with Weynand [10]

4 Derivation of steel and composite beam characteristics on the *model level*, approach 1

Measurements of the deformation capacity of steel and composite beams are normally performed based on a three-point load test [11, 12, 13], see Fig. 8.

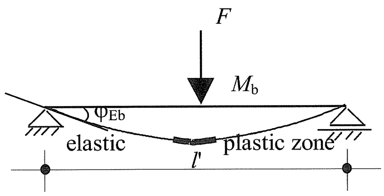

Fig. 8: Three-point load test.

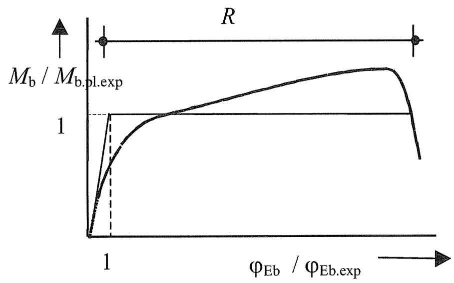

Fig. 9: Test moment-rotation curve of three-point load test. The definition of deformation capacity R is plotted.

The test results are plotted dimensionless. The rotation ϕ_{Eb} at the beam-ends is expressed dimensionless by dividing by the elastic rotation $\phi_{Eb.exp} = F_p l'^2/16EI_s$ of the beam-ends under the plastic load F_p. The moment in the beam span ($M_b = {}^1/_4\, F\, l'$) is expressed dimensionless by dividing by the plastic moment capacity ($M_{b.pl.exp} = {}^1/_4\, F_p\, l'$). This yields Fig. 9. The schematisation on the model level is also represented in Fig. 9, including the definition of deformation capacity R. The determination of the plastic moment capacity of the beam $M_{b.pl.exp}$ is ambiguous. Questions are for instance if the plastic moment capacity is based on measured values, as done in [11] or on a theoretical model. Furthermore, in case of steel beams there is agreement about the model to determine the plastic moment capacity (based on a rigid plastic stress distribution). However, in case of composite beams, a variety of models exist, all leading to different predictions.

5 Parameter study

5.1 Objective

As already mentioned in the introduction, the objective of the study reported in this paper is to make a comparison between the bearing capacity of real structures (*test level*) and the bearing capacity of these structures based on an elastic-plastic model (*model level*). This enables one to draw conclusions on the different definitions for resistance, stiffness and deformation capacity.

The comparison is made for a steel-concrete composite beam system, see Fig. 10:

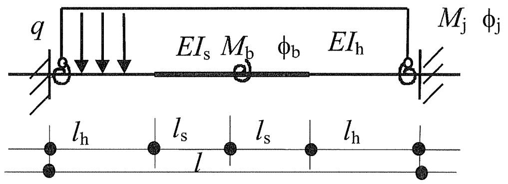

Fig. 10: Composite beam system.

For simplicity it is assumed that, if the bending moment at the section in mid-span exceeds a certain level, all plastic deformations are concentrated in this section. In other words, a plastic hinge occurs. The rest of the beam is assumed to behave elastically. The stiffness of the beam is different in the range where hogging moments occur (EI_h) and the range where sagging moments occur (EI_s) [14, 15]. The effect of residual stresses due to un-propped construction in the phase of concrete curing is outside the scope of this investigation.
The characteristics of the system are described by a set of 19 parameters. The moment rotation curve of the joints is described by 8 parameters, which are indicated in Fig. 11 by the boxed parameters. This figure also shows that in the parameter study three fixed ratios between properties have been adopted. These ratios are indicated by $2x$:x, y:y and z:$3z$. Furthermore, calculations are terminated if the moment in the descending branch is lower than 0,5 $M_{j.pl.exp}$.

The non-linear properties of the spring at mid-span are derived according to the procedure given in Annex A. In this procedure, the spring properties are derived from a three-point load test. This test results in a moment (M_b) - end rotation (ϕ_{Eb}) curve, in shape similar to the one of Fig. 11. In this case, 9 parameters are required to describe the curve, because the initial stiffness is equal to 4 El_s/l', where EI_s is the beam stiffness for sagging moments and l' is the span of three point load test, according to Fig. 8.
With the span of the composite beam l and the beam stiffness for hogging moment EI_h together with the already mentioned beam stiffness for sagging moments EI_s the behaviour of the beam can be described.
In paragraph 5.2 it is described how the non-linear behaviour of the system of Fig. 10 can be determined, based on a combination of elementary mechanics and a Newton-Raphson approach. Paragraph 5.3 explains how values for the set of 19 parameters are selected. A worked example of the calculation procedure is given in paragraph 5.4. The calculation procedure is checked with a simple user-interface as described in paragraph 5.5. Paragraph 5.6 explains how the parameter study is carried out, with the results given in paragraph 5.7.

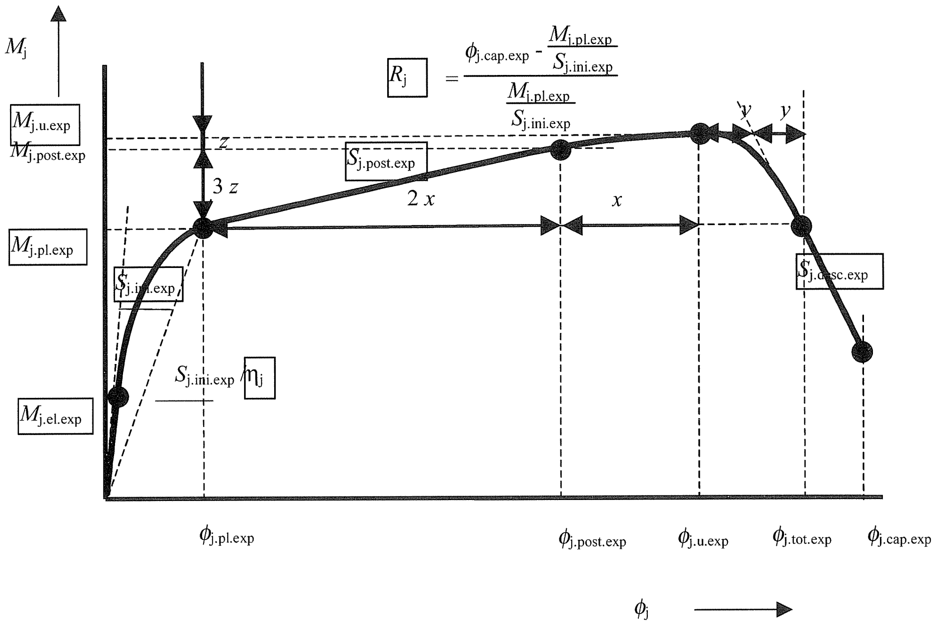

Fig. 11: M_j-ϕ_j curve of a joint.

5.2 Behaviour of the system based on test curves

Assume that non-linear characteristics of the joints and the beam hinge are considered. In that case, the following equations hold:

$$M_j = f(\phi_j) \tag{1}$$

$$M_b = f(\phi_b) \tag{2}$$

In other words, the moment M_j in the joint is a (non-linear) function of the joint rotation ϕ_j. An example of such a non-linear function is given in Fig. 11. The moment M_b in the beam is a (non-linear) function of the beam hinge rotation ϕ_b.

Equilibrium in the system is achieved in case:

$$M_b + M_j = \tfrac{1}{8} q\, l^2 \tag{3}$$

Furthermore, a constitutive relation can be derived for the angular rotation at mid span of the beam where possibly a plastic hinge will form:

$$- \quad M_b \left(\frac{l_h}{EI_h} + \frac{l_s}{EI_s}\right) - \tfrac{1}{2}\phi_b + q\left(\frac{l_h^3}{6\,EI_h} + \frac{l_h^2 l_s}{2\,EI_h} + \frac{l_h l_s^2}{2\,EI_h} + \frac{l_s^3}{6\,EI_s}\right) + \phi_j = 0 \tag{4}$$

In this equation l_s is half of the total beam length where sagging moments occur, l_h is half of the total beam length where hogging moments occur (see Fig. 10), q is the uniformly distributed load on the beam:

$$l_s = \sqrt{\frac{M_b}{M_b + M_j}}\ \tfrac{1}{2}\, l \tag{5}$$

$$l_h = \tfrac{1}{2}\, l - l_s \tag{6}$$

The deflection in the mid span of the beam of Fig. 10, based on elementary mechanics, is then:

$$\delta_{mid} = - M_b \left(\frac{l_h^2}{2\,EI_h} + \frac{l_h l_s}{EI_h} + \frac{l_s^2}{2\,EI_s}\right) + q\left(\frac{l_h^4}{8\,EI_h} + \frac{l_h^3 l_s}{2\,EI_h} + \frac{3\, l_h^2 l_s^2}{4\,EI_h} + \frac{l_h l_s^3}{2\,EI_h} + \frac{l_s^4}{8\,EI_s}\right) + \phi_j\,(l_h + l_s) \tag{7}$$

There are four possible failure modes:

1. lack of deformation capacity of the joint;
2. lack of deformation capacity in the member;
3. lack of bearing capacity of the system;
4. ultimate limit state controlled by excessive deformations.

The fourth criterion is used by Bijlaard [16], by defining that the load, occurring at a deformation δ_{mid} equal to δ_{lim} = 1/50 times the beam span, may be considered as the ultimate load of the system. In Fig. 12, four examples are given of load (q)-deformation (δ_{mid}) curves of the system given in Fig. 10. Each of the examples shows a typical failure mode of the system.

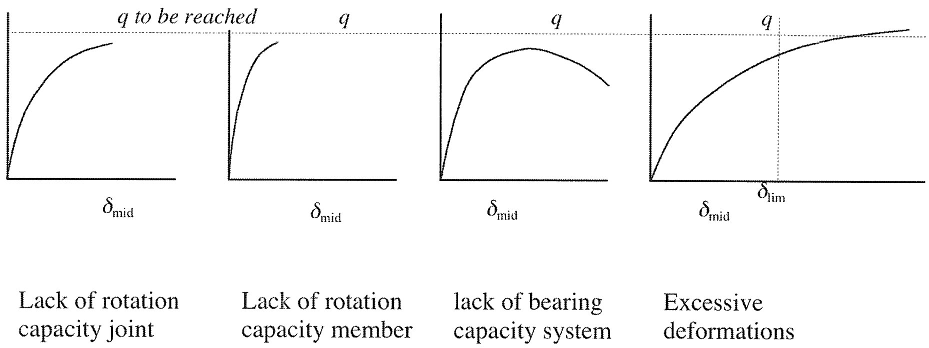

Fig. 12: Different failure modes in beam system.

The load (q)-deformation (δ_{mid}) curve is determined based on eq. (1) to (7) with an incremental calculation procedure. The selected calculation procedure is based on a Newton-Raphson approach. It copes with the non-linear spring characteristics and sudden unloading of the system. During each load step, the elastic beam stiffness is adjusted based on the moment distribution in the beam. Generally, the elastic beam stiffness for hogging moments is lower than for sagging moments. During each incremental step it is checked if one of the failure modes occurs.

5.3 Parameter set

The non-linear model of the beam system, as described in the previous paragraph, should be fed with data to allow a comparison between the generated tests and the bilinear approximations on the *model level*. The following parameter set is chosen, see Tab. 2:

Table. 2: Nineteen parameters varied in the study

Parameter	Lower value	Upper value	Unit	Parameter	Lower value	Upper value	Unit
l	7	12	m	$\frac{EI_s}{(M_{b.pl.exp} + M_{j.pl.exp})\, l}$	4	20	[-]
$\frac{M_{j.pl.exp}}{M_{b.pl.exp}}$	0,2	0,8	[-]	$\frac{S_{j.ini.exp}\, l}{EI_h}$	0,5	20	[-]
$\frac{8\,(M_{b.pl.exp} + M_{j.pl.exp})}{l^2}$	20	100	kN/m	$\frac{M_{j.u.exp}}{M_{j.pl.exp}}$	1,05	1,5	[-]
$\frac{EI_h}{EI_s}$	0,5	1	[-]	$\frac{M_{b.u.exp}}{M_{b.pl.exp}}$	1,05	1,3	[-]
$\frac{M_{j.el.exp}}{M_{j.pl.exp}}$	0,35	0,9	[-]	$\frac{S_{j.post.exp}}{S_{j.ini.exp}}$	0,015	0,25	[-]
$\frac{M_{b.el.exp}}{M_{b.pl.exp}}$	0,25	0,7	[-]	$\frac{S_{Eb.post.exp}}{S_{Eb.ini.exp}}$	0,04	0,15	[-]
η_j	1,25	3,5	[-]	$\frac{S_{j.desc.exp}}{S_{j.ini.exp}}$	-0,04	-0,4	[-]
η_b	1,25	3	[-]	$\frac{S_{Eb.desc.exp}}{S_{Eb.ini.exp}}$	-0,04	-0,4	[-]
R_j	2,5	15	[-]	R_b	1	15	[-]
$\frac{l'}{l}$	0,7	1	[-]				

The ranges of the parameters $\frac{M_{j.el.exp}}{M_{j.pl.exp}}, \frac{M_{j.u.exp}}{M_{j.pl.exp}}, \frac{S_{j.post.exp}}{S_{j.ini.exp}}, \frac{S_{j.desc.exp}}{S_{j.ini.exp}}$ and η_j have been confirmed with tests on composite joints [17, 18, 19, 20, 21, 22, 23, 24]. Furthermore, tests on beams [25, 26, 27] have been used to confirm the ranges of $\frac{M_{b.el.exp}}{M_{b.pl.exp}}, \frac{M_{b.u.exp}}{M_{b.pl.exp}}, \frac{S_{Eb.post.exp}}{S_{Eb.ini.exp}}, \frac{S_{Eb.desc.exp}}{S_{Eb.ini.exp}}$ and η_b.

Some notes should be made on the confirmation of the parameters based on tests:

1. In many cases, it is difficult to assess a value for the post-limit-stiffness from a test, because of absence of a specific post-limit stiffness branch.
2. The descending branch of a curve is absent in a number of cases. Then, no data are obtained.
3. A number of tests have been stopped before reaching failure because of large displacement of the test rig. It is assumed that this does not really affect the outcome of the parameter study, because mostly deformations are beyond 40 milliradians, causing a beam deflection of more than 1/50 times the beam span.
4. To obtain joint rotations from a test, different procedures were followed. For instance, Aribert and Lachal [18] determined the rotation of the joint by measuring the vertical displacement of the test specimen. From this vertical displacement, the rotation is deduced. On the other hand, Anderson and Najafi [17] determined the joint rotation by measuring the rotations of the steel beam relative to the vertical axis through the centroid of the column section with two transducers. These procedures possibly will lead to different readings of the rotations, since in the procedure of Aribert and Lachal the slip between steel beam and concrete slab is taken into consideration and in the case of Anderson and Najafi only the steel beam rotations are measured. The effect of the difference in measuring procedure possibly needs further attention.
5. The effect of a moment gradient on the moment (M_b) - end rotation (ϕ_{Eb}) curve of a beam in a three-point load test is not investigated. Possibly, some further research needs to be done on this aspect.

The ranges of other parameters are based on an engineering assessment, in particular:
1. The parameter l of the system of Fig. 10 is taken between 7 and 12 meter as a practical range.
2. The uniformly distributed load q at the system of Fig. 10 is taken between 20 and 100 kN/m as a practical range. The value of q is approximately: $\frac{8\,(M_{b.pl.exp} + M_{j.pl.exp})}{l^2}$, see Tab. 2.
3. The bounds $4 < \frac{EI_s}{(M_{b.pl.exp} + M_{j.pl.exp})\,l} < 20$ are a serviceability limit state criterion based on the fact that beam deflections should be limited. The serviceability check in the elastic stage is:

$$\alpha_1 \frac{\frac{q}{\alpha_2} l^4}{EI_s} < \frac{l}{\alpha_3} \tag{8}$$

where:

α_1 = a factor, for instance $\frac{5}{384}$ for a prismatic beam and pinned joints;
α_2 = the ratio, for instance 1,5, between q in ULS and in SLS;
α_3 = a factor, for instance 250.
q = load in ULS, $q \approx \frac{8\,(M_{b.pl.exp} + M_{j.pl.exp})}{l^2}$

This can be rewritten to:

$$\frac{EI_s}{(M_{b.pl.exp} + M_{j.pl.exp})\,l} = \frac{8\,\alpha_1\,\alpha_3}{\alpha_2} \tag{9}$$

By adopting the bounds $4 < \frac{EI_s}{(M_{b.pl.exp} + M_{j.pl.exp})\,l} < 20$ a practical range is covered.

The curves between the different points described by the parameter set are taken as elliptic.

5.4 *Worked example*

A worked example of the procedure given above is as follows. Assume the set of parameters given in Tab. 3. From Tab. 3 the parameters given in Tab. 4 can be resolved.

Table. 3: Sample parameters

Parameter	**Value**	**Unit**	**Parameter**	**Value**	**Unit**
l	9,85	m	$\frac{EI_s}{(M_{b.pl.exp} + M_{j.pl.exp})\, l}$	15,68	[-]
$\frac{M_{j.pl.exp}}{M_{b.pl.exp}}$	0,72	[-]	$\frac{S_{j.ini.exp}\, l}{EI_h}$	14,74	[-]
$\frac{8\,(M_{b.pl.exp} + M_{j.pl.exp})}{l^2}$	58,4	kN/m	$\frac{M_{j.u.exp}}{M_{j.pl.exp}}$	1,33	[-]
$\frac{EI_h}{EI_s}$	0,93	[-]	$\frac{M_{b.u.exp}}{M_{b.pl.exp}}$	1,19	[-]
$\frac{M_{j.el.exp}}{M_{j.pl.exp}}$	0,55	[-]	$\frac{S_{j.post.exp}}{S_{j.ini.exp}}$	0,15	[-]
$\frac{M_{b.el.exp}}{M_{b.pl.exp}}$	0,62	[-]	$\frac{S_{Eb.post.exp}}{S_{Eb.ini.exp}}$	0,10	[-]
η_j	2,56	[-]	$\frac{S_{j.desc.exp}}{S_{j.ini.exp}}$	-0,054	[-]
η_b	1,83	[-]	$\frac{S_{Eb.desc.exp}}{S_{Eb.ini.exp}}$	-0,22	[-]
R_j	15	[-]	R_b	15	[-]
$\frac{l'}{l}$	1	[-]			

With this set of parameters, the behaviour of the beam-system given in Fig. 10 can be determined. The resulting moment (M_j) rotation (ϕ_j) curve of a joint test is given in Fig. 13. The resulting behaviour of the spring at mid span of Fig. 8 is given in Fig. 14. This behaviour is expressed in terms of the moment (M_b) rotation (ϕ_{Eb}) curve of the equivalent beam test. Fig. 15 shows the load (q)-deformation (δ_{mid}) curve of the system of Fig. 10.

Table. 4: Resolved parameters from sample

Parameter	Value	Unit	Parameter	Value	Unit
l	9,85	m	$M_{b.pl.exp}$	297	kNm
$M_{j.pl.exp}$	411	kNm	EI_h	101186	kNm²
EI_s	109390	kNm²	$S_{j.ini.exp}$	163641	kNm/rad
$M_{j.u.exp}$	396	kNm	$M_{b.u.exp}$	489	kNm
$M_{j.el.exp}$	164	kNm	$M_{b.el.exp}$	228	kNm
η_j	2,56		η_b	1,83	
$S_{j.post.exp}$	25143	kNm/rad	$S_{Eb.ini.exp}$	44422	kNm/rad
$S_{Eb.post.exp}$	4562	kNm/rad	$S_{j.desc.exp}$	-8902	kNm/rad
$S_{Eb.desc.exp}$	-9613	kNm/rad	$\phi_{j.post.exp}$	0,008	rad
$\phi_{Eb.post.exp}$	0,030	rad	$\phi_{j.u.exp}$	0,010	rad
$\phi_{Eb.u.exp}$	0,038	rad	$\phi_{j.tot.exp}$	0,032	rad
$\phi_{Eb.tot.exp}$	0,055	rad	l'	9,85	m

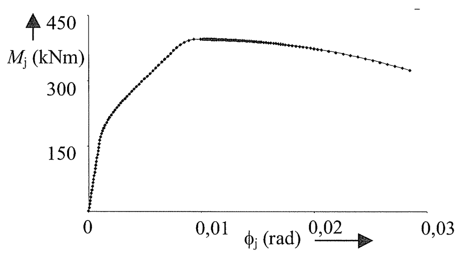

Fig. 13: Resulting moment (M_j) rotation (ϕ_j) curve of a joint test (based on parameters of table 4)

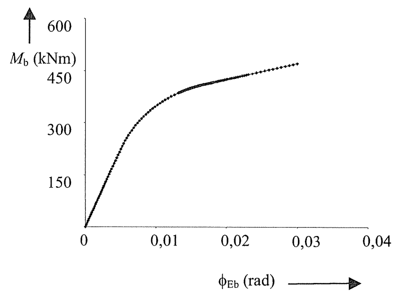

Fig. 14: Resulting moment at mid span (M_b) beam end rotation (ϕ_{Eb}) curve of a beam test

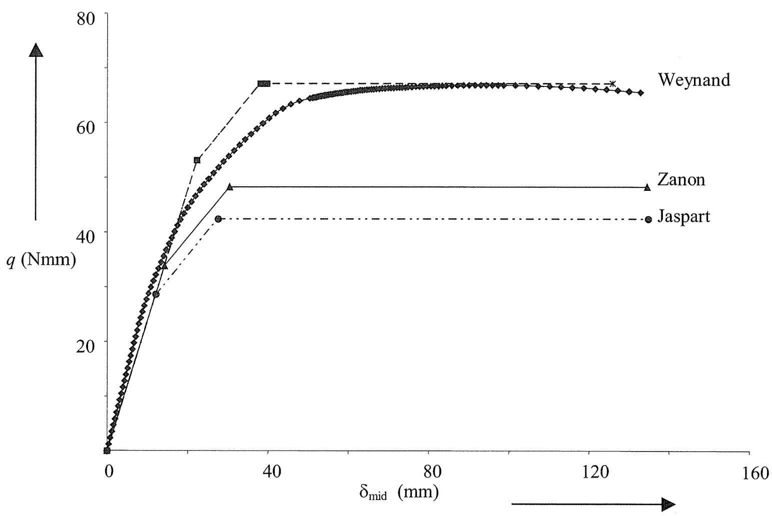

Fig. 15: Load (q)-deformation (δ_{mid}) curve

Fig. 15 also gives the load deflection behaviour on the *model level* based on the definitions adopted by various authors. The results produced with the definitions of Crisinel & Kattner have not been reported in this example. In the elastic-plastic calculations on the *model level*, for the elastic stiffness of the joint, half of the initial joint stiffness has been adopted, in accordance with Eurocode 3 [4] and 4 [5]. The ratio between ultimate load at *test level* (q_{test}) and the load at *model level* (q_{model}) is taken as a reference. Based on this ratio, parameter studies are carried out.

5.5 Check of the implemented calculation procedure

The 19 parameters of Tab. 2 have an influence on the ratio between maximum load at *test* and *model level*. In this parameter study, these parameters are combined as independent variables, leading to many possibilities. It is important to get confidence in the computer tool used to calculate this ratio. Due to the non-linear character of the calculation (non-linear springs and different beam stiffnesses for hogging and sagging), convergence problems may occur.

In EXCEL, a simple user-interface is developed to check the implemented calculation procedure and to determine the number of load steps in the incremental procedure. Fig.16 shows a screen dump. On the left-hand side of the screen, there are slide bars, which can be used to select a value for the different parameters. After dragging one of the slides, the non-linear calculation of the load-deflection behaviour of the system of Fig. 10 is carried out. Furthermore, the resistance and deformation capacity of the beam and joints according to the various definitions given in literature are determined. With help of these data, the load-deflection curves on these model characteristics are established. On the right hand side of the screen dump, the ratio between load on *test level* and *model level* according to Jaspart [6], Zanon & Zandonini [8], Weynand [10] and the combination of Weynand and Crisinel & Kattner [9] are reported. At the left-hand side bottom of the screen dump, the failure mode of the system is reported.

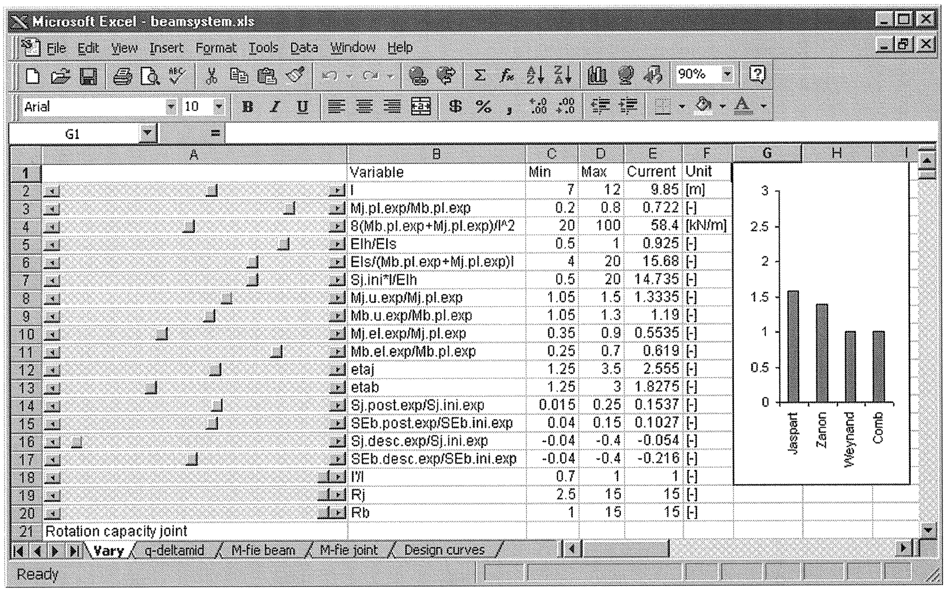

Fig. 16: Screen dump of the tool used to manually investigate the effect of the parameters on ultimate load ratio q_{test}/q_{model}.

The computer tool is used to get confidence in the model and impressions of the effect of parameters on the ratio between test level and model level. This is however studied in a more rational way as described in the next section.

5.6 Set up of parameter study

If for all 19 parameters a minimum of two values is selected, the total number of simulations to be made is at least 2^{19} = 524.288. It is impossible to conclude from such a number of comparisons which definitions of strength and deformation capacity are preferred.
Therefore, for each parameter, a random variable is chosen based on a uniform distribution. The range of this distribution for each parameter is given in Tab. 2. Then, a calculation is carried out of the maximum load at the system q_{test} at the *test level* and the maximum load q_{model} at the *model level*. This is repeated 5000 times. Then an estimate is made of the average μ and standard deviation σ of the ratio between q_{test} versus q_{model}. This number of calculations gives an error of less then 3% on the estimate of μ with a reliability of 95% [28].

In a second stage, the same procedure is carried out, but for one parameter a fixed value is set. This is done 5 times for each parameter, resulting in 19 times 5 times 5000 calculations. During each calculation, the estimate of the average μ and standard deviation σ is determined. This enables to study the sensibility of the various definitions for strength and rotation capacity to the different parameters.

5.7 Results

The presentation of Eurocode 3 Annex Z is used to make a comparison between *test level* and *model level*. In case of the definition given by Jaspart, this is given in Fig. 17. A point with co-ordinates (q_{model}, q_{test}) in Fig. 17 represents one calculation. The results of 5000 calculations are given. Fig. 17 also shows the line $q_{\text{model}} = q_{\text{test}}$. In a number of cases, the model prediction is above the test.

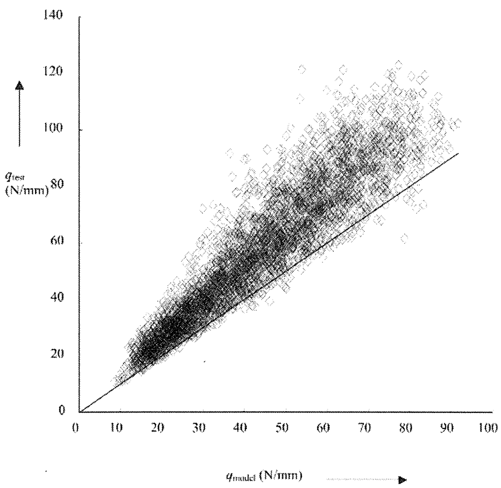

Fig. 17: Results of maximum load q (N/mm) predictions, test versus model level according to Jaspart.

Tab. 5 reports the average μ and standard deviation σ of the ratio between q_{test} versus q_{model} for all investigated definitions. The definition of Jaspart [6] gives the largest average ratio between the test and model, but also the largest standard deviation. The definition of Zanon & Zandonini [8] is close to the one of Jaspart. Furthermore, the other three definitions by Crisinel & Kattner [9] and Weynand [10] and the combination of the Weynand and Crisinel & Kattner provide a smaller average ratio and also a smaller variation. For some definitions, the average μ is below or equal to 1. This is due to the overestimate of the joint stiffness as $S_{\text{j.ini}}$ / 2 and the beam stiffness as pure elastic in the model calculations [5]. From Tab. 5 it can be concluded that the definitions of Crisinel & Kattner, Weynand or the combination between these two are preferred above the definitions of Jaspart and Zanon & Zandonini.
The difference between the definition of Weynand and the combination of Weynand and Crisinel & Kattner is marginal.

Tab. 5: Estimate of average μ and standard deviation σ of q_{test} versus q_{model}.

Method	**Estimate μ**	**Estimate σ**
Jaspart	1.32	0.21
Zanon & Zandonini	1.20	0.16
Weynand	1.00	0.10
Crisinel & Kattner	0.95	0.09
Combination of Weynand and Crisinel & Kattner	0.99	0.10

Fig. 18 shows typical results of calculations with a fixed parameter. In this case, the results for the parameter beam length l are given. In the figure, for 5 values of the parameter l, results are plotted. For each definition (Jaspart, Weynand etc.), the 95% confidence interval for the ratio $q_{\text{test}} / q_{\text{model}}$ is given. The confidence interval is calculated as $\mu \pm 1{,}65\ \sigma$. The impact of the values of the beam length on the confidence interval can be monitored in this figure.
Fig. 18 shows that the beam length l virtually has no influence on the confidence interval. This is valid for all definitions.
In Fig. 19, the moment ratio $\frac{M_{\text{j.u.exp}}}{M_{\text{j.pl.exp}}}$ is varied. The confidence intervals calculated based on definitions of Jaspart and Zanon & Zandonini are sensitive to changes in the ratio $\frac{M_{\text{j.u.exp}}}{M_{\text{j.pl.exp}}}$. This could be expected because a higher ultimate moment $M_{\text{j.u.exp}}$ in a joint will lead to a higher maximum load q_{test} on the beam system. This ultimate moment in a joint does however not affect the calculated joint resistance according to the definitions of Jaspart and Zanon & Zandonini.
The other 17 parameters have been investigated in a similar way [29]. A summary of the variation of the confidence interval of all 19 parameters is given in Fig. 20. The variation of the confidence interval is calculated with formula (10):

$$\max_{j=1\,to\,4}\left(\frac{|\mu_j-\mu_{j+1}+1{,}65(\sigma-\sigma_{j+1})|}{\mu};\frac{|\mu_j-\mu_{j+1}-1{,}65(\sigma-\sigma_{j+1})|}{\mu}\right) \tag{10}$$

In this formula 4 times the difference between two adjacent confidence intervals is determined. This difference is divided by μ, the average of the 5 values, which have been investigated per parameter. For instance, Fig. 20 shows that the value, which is determined according to formula (10) in case of the definition of Jaspart, is smaller for the beam length l (Fig. 18) than for the moment ratio $\frac{M_{j.u.exp}}{M_{j.pl.exp}}$ (Fig. 19). So the confidence intervals of Fig. 18 differ less than those of Fig. 19.

Based on these parameter variations, the following observations can be made:

- the definitions of Jaspart and Zanon & Zandonini show change in confidence interval with variation of the parameters $\frac{M_{j.u.exp}}{M_{j.pl.exp}}$, η_j, $\frac{M_{j.el.exp}}{M_{j.pl.exp}}$, $\frac{S_{j.post.exp}}{S_{j.ini.exp}}$ and $\frac{S_{Eb.post.exp}}{S_{Eb.ini.exp}}$. This shows that these definitions are dependent on moment rotation characteristics, like the post-limit stiffness, which are not determining the behaviour of the beam system;
- change in $\frac{S_{Eb.desc.exp}}{S_{Eb.ini.exp}}$ has virtually no effect on the confidence intervals for all definitions. This is because the descending branch is not very pronounced in the beam tests;

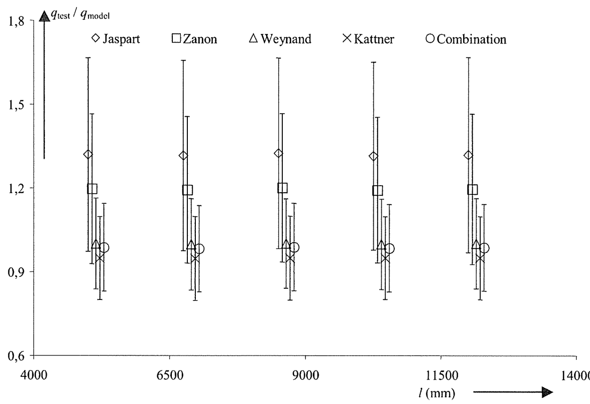

Fig. 18:
95% confidence interval for variation in l

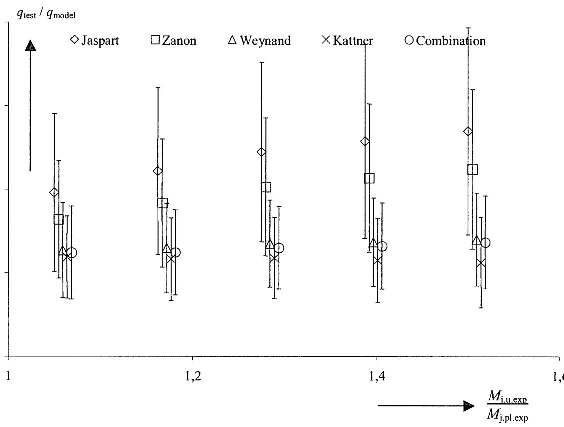

Fig. 19:
95% confidence interval for variation in $\frac{M_{j.u.exp}}{M_{j.pl.exp}}$

- changes in $\frac{EI_h}{EI_s}$ and $\frac{l'}{l}$ also have no effect on the confidence intervals;
- change in $\frac{S_{j.desc.exp}}{S_{j.ini.exp}}$ has only effect on change in the confidence intervals for the definition according to Weynand or the combination between Crisinel & Kattner and Weynand. The cause of this needs further investigation;
- values of R_j and R_b around 1 to 3 give smaller confidence intervals than larger values (see [29]).

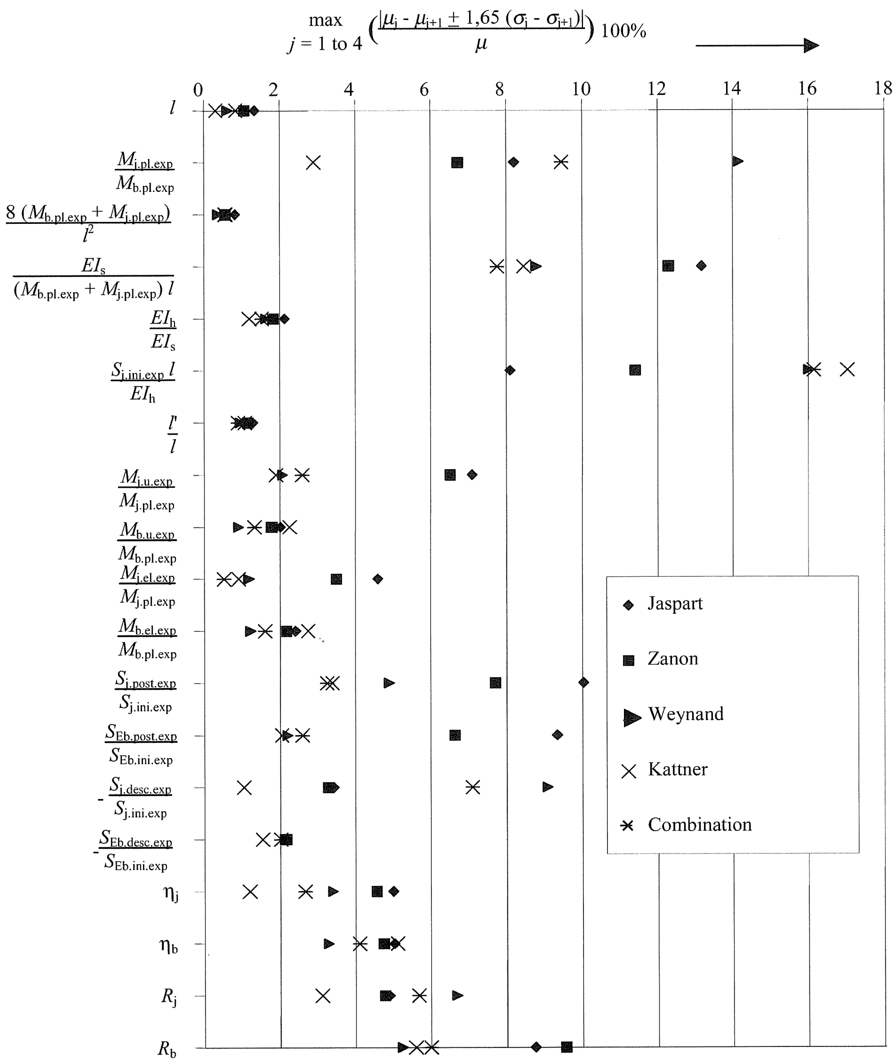

Fig. 20: Summary of variation of confidence interval for all 19 parameters according to formula (10)

6 Conclusions and recommendations

From the investigation reported in this paper, a number of conclusions can be drawn:

1. A distinction can be made between *test level*, *model level* and *design level*. In this paper different definitions for resistance and deformation capacity for composite beams and joints at *model level* have been studied.
2. The effect of 19 parameters, describing a composite beam system, on the ratio between maximum beam load on *test* and *model level*, determined according to 5 definitions, has successfully been investigated by means of a computer tool. This computer tool generates test curves, which have been compared with approximations on the model level.
3. About 5000 generated tests are required to determine an accurate estimate of the average ratio between maximum load of the investigated composite beam system on the *test level* and the *model level* and the corresponding standard deviation.
4. The definitions of Weynand and Crisinel & Kattner or the combination between these two give the smallest standard deviation in results. Therefore, they are preferred above the definitions of Jaspart and Zanon & Zandonini.
5. The difference in average ratio and standard deviation between the definition of Weynand and the combination of Weynand and Kattner is marginal.
6. The strength and deformation capacity according to the definitions of Jaspart and Zanon & Zandonini are dependent on properties which are not determining for the behaviour of the beam-system on the *test level*. This is the cause of scatter in the ratio between the maximum load at *test level* and at *model level*.
7. Small values of deformation capacity R_j and R_b, in practice caused by a brittle failure mode like fracture of rebars, show smaller confidence intervals than larger values.

The following recommendations are made:

1. It is recommended to investigate other possibilities than the modelling of the joint stiffness with $S_{j.ini}$ / 2 and the modelling of the beam plasticity with a rigid plastic spring on the model level. Based on observations with the developed software, it is expected that the average q_{test}/q_{model} ratio could be well above 1 in all cases.
2. It is recommended to focus further investigations on the definitions of Weyand, Crisinel & Kattner or the combination between those two, because the definitions of Jaspart and Zanon & Zandonini give larger standard deviations compared to the others.
3. It is recommended to do further research on the question whether or not the descending branch should be included in the definition of deformation capacity. This study indicates that the descending branch is insignificant. Since this property is difficult to assess, it could be easier to use a definition where the deformation capacity is taken as the rotation at the peak level of the moment rotation curve.

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Annex A: Equivalent spring model for a beam

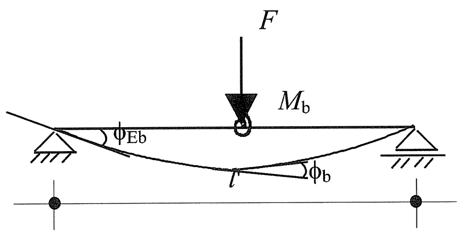


Fig. 21: Equivalent elastic beam with a rotational spring and a single load at mid span.

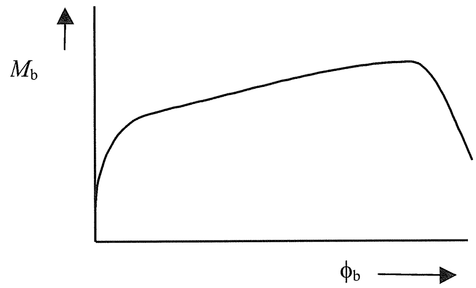


Fig. 22: Equivalent rotational spring characteristic for the system of Fig. 21.

Fig. 21 shows a system where it is assumed that the beam behaves elastically and that there is a rotational spring at mid span. Assume now that the beam system of Fig. 8 has the same moment M_b, rotation ϕ_{Eb} curve as the beam of Fig. 21. The following relation should be valid:

$$\phi_{Eb} = \tfrac{1}{2}\,\phi_b + \frac{F\,l'^2}{16\,EI_s} = \tfrac{1}{2}\,\phi_b + \frac{M_b\,l'}{4\,EI_s} \tag{11}$$

In this equation, $^1/_2\,\phi_b$ is the contribution of the non-elastic spring rotation to the beam end rotation and $\frac{F\,l'^2}{16\,EI_s}$ is the elastic beam end rotation based on elementary mechanics.

Rewriting gives:

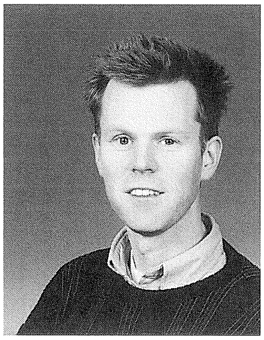
$$\phi_b = 2\,\phi_{Eb} - \frac{M_b\,l'}{2\,EI_s} \tag{12}$$

Since $\phi_{Eb.exp} = \frac{M_{b.pl.exp}\,l'}{4\,EI_s}$ (the elastic beam end rotation under $M_{b.pl.exp}$), the following relation is valid:

$$\phi_b = \frac{M_{b.pl.exp}\,l'}{2\,EI_s}\left(\frac{\phi_{Eb}}{\phi_{Eb.exp}} - \frac{M_b}{M_{b.pl.exp}}\right) \tag{13}$$

Equation (12) or (13) can be used to derive a moment M_b rotation ϕ_b curve for the spring at mid span of the beam, that is shown in Fig. 21. An example of the shape of such a curve, based on the moment $\frac{M_b}{M_{b.pl.exp}}$ rotation $\frac{\phi_{Eb}}{\phi_{Eb.exp}}$ curve of Fig. 9, is given in Fig. 22.

In Memoriam Martin Steenhuis (1962-2001)



During his holidays near Briançon in the French Alps, Martin Steenhuis died on August 3, 2001 due to a canoeing accident on the river Durance.
Christiaan Martinus Steenhuis was born April 14, 1962 in Stadskanaal, The Netherlands. After his graduation from high school, he studied Structural Design at Eindhoven University of Technology in The Netherlands where he graduated in 1988. He then joined TNO Bouw to become a researcher and he was very active in the field of steel structures, especially structural connections in building frames. He contributed substantially to the introduction of the utilisation of partial strength, semi-rigid joints in the building practice through numerous publications, his participation in technical committees (secretary of Bouwen met Staal TC10a and ECCS TC10) and through his code drafting activities. He was involved in the drafting process of 'Eurocode 3, Design of Steel Structures, Part 1.8, Design of Joints'. Martin Steenhuis also was active in The Netherlands contributing to special (post-graduate) courses on steel structures, connections and stability, organised by Bouwen met Staal. Through these activities he gradually discovered his affinity to teaching and when the opportunity came, he decided to move to Eindhoven University of Technology, The Netherlands, to become Assistant Professor, broadening his scope to structural design in general. He started on August 1, 1999 with tremendous enthusiasm and energy. Apart from continuing his activities in the field of structural steel connections, he supervised first year students carrying out their projects and made them enjoy structural design in the process. He also lectured on structural safety and he was one of the first teachers to use the computer for exams. Students would pick up their exam from the Internet and, after completion, send it back to him for checking. Soon after starting at Eindhoven University of Technology, he made it known that he wanted to work on a PhD-thesis provisionally entitled 'The influence of deformation capacity on the reliability of steel and composite building structures'. Thus, he combined his two main professional topics of interest: structural connections and structural safety. After only two years on the project, he almost completed the deterministic part of his PhD-project (the final paper of this part is now published in this volume of Heron). The next step would have been to continue with the probabilistic part of his PhD-project. Unfortunately he never started this due to his tragic canoeing accident. We, his supervisors and co-authors of the Heron-paper, are confident that he would have finished his PhD-project successfully and on time. We lost in Martin Steenhuis an independent researcher, an enthusiastic teacher and a great colleague and friend.