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Recommendations on imperfections in the design of plated structural elements of bridges

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ABSTRACT

High-yield strength steel-plated structures represent competitive solutions when used in steel and steel–concrete composite bridges. Nevertheless, further modifications may still be introduced at the design stage in the case of slender sections, in order to minimize the number of their stiffeners and thereby economize on manufacturing costs. Eurocode 3 "Design of steel structures" specifies design methodologies for slender plates subjected to compression and for stiffeners. Moreover, the use of Finite Element Method (FEM) software is fast becoming an alternative analytical method for the design of complete structures or structural elements, as it offers a more realistic approach. This paper makes recommendations for FEM assessments of plated sections in bridges that take the initial imperfections, geometric imperfections and residual stresses of the sections into account, in order to arrive at realistic results.

1. Introduction

Steel structures are in general widely employed in civil and other construction works. However, new technological advances have led to innovative changes in their use that range from the development of high-strength steels [1], through innovation in the fabrication of steel components based on welding, cold and hot forming processes, new methods for the erection of steel structures, and the use of advanced calculation methods thanks to new software and computing capabilities. Steel structures compete alongside other structural materials and have to maintain competitive fabrication and erection costs, and associated time schedules. All of the above have led to the design of lighter, slenderer structural solutions for steel structures and steel components; decisive factors that create a need for further in-depth studies of their stability.

The competitive advantage of steel and steel–concrete composite bridges as opposed to concrete-based solutions has to be demonstrated for each project. There is little or no general agreement and the competitiveness of one technique over another depends on multiple factors: main spans of between 50 and 125 m (typical in steel and steel–concrete composite bridges), the specific project, site conditions local construction firm capabilities, manpower rates versus material costs, and so on.

Nevertheless, widely acknowledged strategies guarantee the competitiveness of steel-based structural solutions:

- Minimization of the material used in the structure; e.g. use of high strength steels.
- Optimization of the structural design; e.g. consideration under service stage loads as much as the fabrication and initial bridge launching stage, and reduction of the self-weight of the bridge in the launching phase, all lead to the minimization of actions in the construction phase.
- Reduction of fabrication costs; e.g. simplification of the plated sections by reduction of the stiffening, in order to minimize welding costs.

In summary, there is a need for slenderer solutions and plated components that are easier to fabricate. However, this approach requires careful and detailed analysis of the relevant structural solutions, to guarantee safety in the construction and service stages; more specifically, analysis of the compression resistance of slenderer steel plates.

The development of powerful computers and Finite Element Method (FEM) software applications [2] has reached a point where almost any plated structure can be modelled, regardless of its geometric complexity, its sensitivity to imperfections, and its non-linear behaviour. Thus, the following main issues are more important than ever for the structural engineer: the development of an accurate numerical model (fit to the purpose) and the calculation of a numerical

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result that provides the information needed to define the characteristic strength of each component for safe design that is also competitive.

In FEM analysis, consideration of any initial imperfections is crucial to obtain realistic results that are primarily safe and also competitive, e.g. that reflect the real performance of steel components. The key issue in safe and competitive design is quantitative simulation of imperfections and their influence on plate buckling phenomena.

Annex C: “Finite Element Methods of Analysis — FEM” *of the EN1993-1-5:2005, Eurocode 3:* “Design of steel structures” — *Parts 1–5* “Plated structural elements” [3], provides guidance based on the use of equivalent geometrical imperfections. However, *Annex C* furnishes no comprehensive information on the consideration of residual stress, in addition to geometrical imperfections and the recommendation specifies consideration of equivalent geometrical imperfections. There are, however, few recommendations for designers on the most suitable shapes and the imperfection amplitudes that are relevant to specific steel components subjected to specific types of loading.

This situation led to the inclusion of work package *WP 3.1.:* “Imperfections for FE calculations”, in the COMBRI research project “Competitive steel and composite bridges by innovative steel plated structures” [4]. Its objective was to investigate appropriate strategies to model initial imperfections in the FE calculations of steel-plated structures. In line with Wintersetter and Schmidt [5], three types of approaches were studied, in order to calculate these geometrical imperfections in an FE model:

- REALISTIC: Involves stochastic modelling and extensive measurements; a matter of desired best practice rather than a feasible design option.
- WORST: Worst possible imperfection pattern. It is common practice to use the 1st eigenmode, or a combination of eigenmodes. It is important to note that single dimple imperfections may be worse than eigenmode patterns, in the case of non-linear pre-buckling behaviour.
- STIMULATING: Choosing an equivalent geometrical imperfection pattern that is as simple as possible for the function that simulates the characteristic physical buckling plate behaviour. In practice, amplitudes have to be calibrated, in accordance with critical modes.

The third approach was selected as the strategy for the development of a methodology to account for both geometrical imperfections and residual stresses, which should be considered for the verification of steel-plated structures for bridges, based on FEM analysis.

This paper presents the results of research conducted within the COMBRI project on the consideration of design imperfections in FEM-based design of steel plates which are subjected to in-plane forces, in plated structural elements of bridges. The results were calculated with the following boundary conditions, established at the beginning of the research:

- To achieve recommendations presented as clear guidelines on the shape (local, global, and combination thereof) and magnitude of geometrical imperfections.
- To establish simple rules based on idealized regular patterns to account for the residual stresses of steel-plated structures in FE models.
- To validate the recommendations and rules with experimental data available from tests performed by several partners in the COMBRI project and from the literature.

The final recommendations for the modelling strategies were prepared by TECNALIA on the basis of numerical studies, to assess the influence of shapes, magnitudes and patterns of geometrical imperfections and residual stresses for several cases of loading and member typologies: a stiffened steel plate under compression and bending, stiffened and unstiffened beams under bending and shear stress, and an unstiffened plated beam under patch loading.

The following principles guided the main strategy for the development of the alternative that is presented in this paper to the *Eurocode 3* [3] recommendation.

- G*eometric imperfection amplitudes*: values based on fabrication tolerances provided in relevant standards [6].
- *Geometric imperfection shapes*: shapes based on the expected failure shape of the component, e. g. obtained by pre-analysis with FEM software.
- Regarding *residual stresses*: simplified rectangular patterns of membrane stresses based on research by Paik and Thayamballi [7], see Fig. 1.

The conclusions and recommendations outlined in the following sections of the paper are linked to a specific steel plated component under a specific type of loading, with a view to the presentation of easy-to-follow guidance for practicing engineers:

1. Stiffened steel plates under compression and bending. Column-type buckling behaviour [8].
2. Shear behaviour and bending interaction of stiffened and unstiffened welded girders [4].
3. I-section plated girder subject to patch loading [4].

2. Stiffened steel plates under compression and bending. Column-type buckling behaviour

In this section, the proposal for alternative recommendations to *Annex C* relating to the consideration of initial imperfections is based on tests described by Grondin et al. [8]. These tests consisted of a steel plate with a T-shaped stiffener. Grondin et al. examined the ultimate peak-load resistance of the steel plated component subjected to in-plane axial compression, in combination with and then without out-of-plane load. Fig. 2 shows the specimen used in the parametric investigation that led to the recommendations on the consideration of initial imperfections.

Fig. 3 shows the comparison of the test curve, resulting from the application of the recommendations in Annex C of the Eurocode 3 [3], in the case of residual stresses and an initial geometric imperfection amplitude of 2.00 mm. The proposal under consideration accurately reflects the explicit residual stresses and geometric imperfections in Eurocode 3.

The final conclusions from this section and the resulting recommendations are presented in Table 1. Two main aspects may be underlined at this point:

1. Although the parametric study has produced good results with amplitudes of a/1000, which represent the typical maximum imperfection for hot-rolled profiles, according to EN1090-2:2004

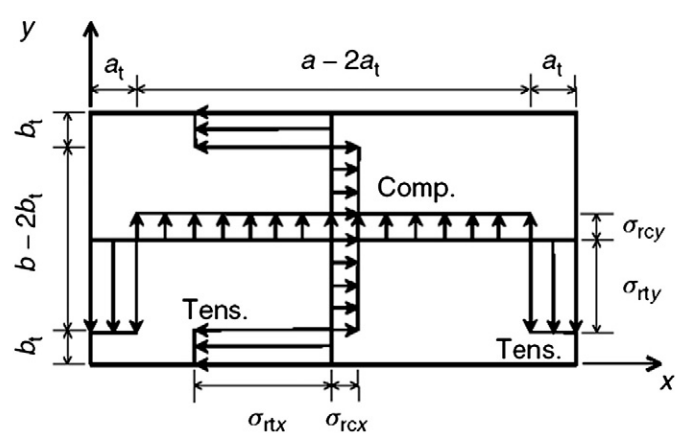

Fig. 1. Simplified patterns of residual stresses based on a rectangular distribution of membrane stresses. [7].

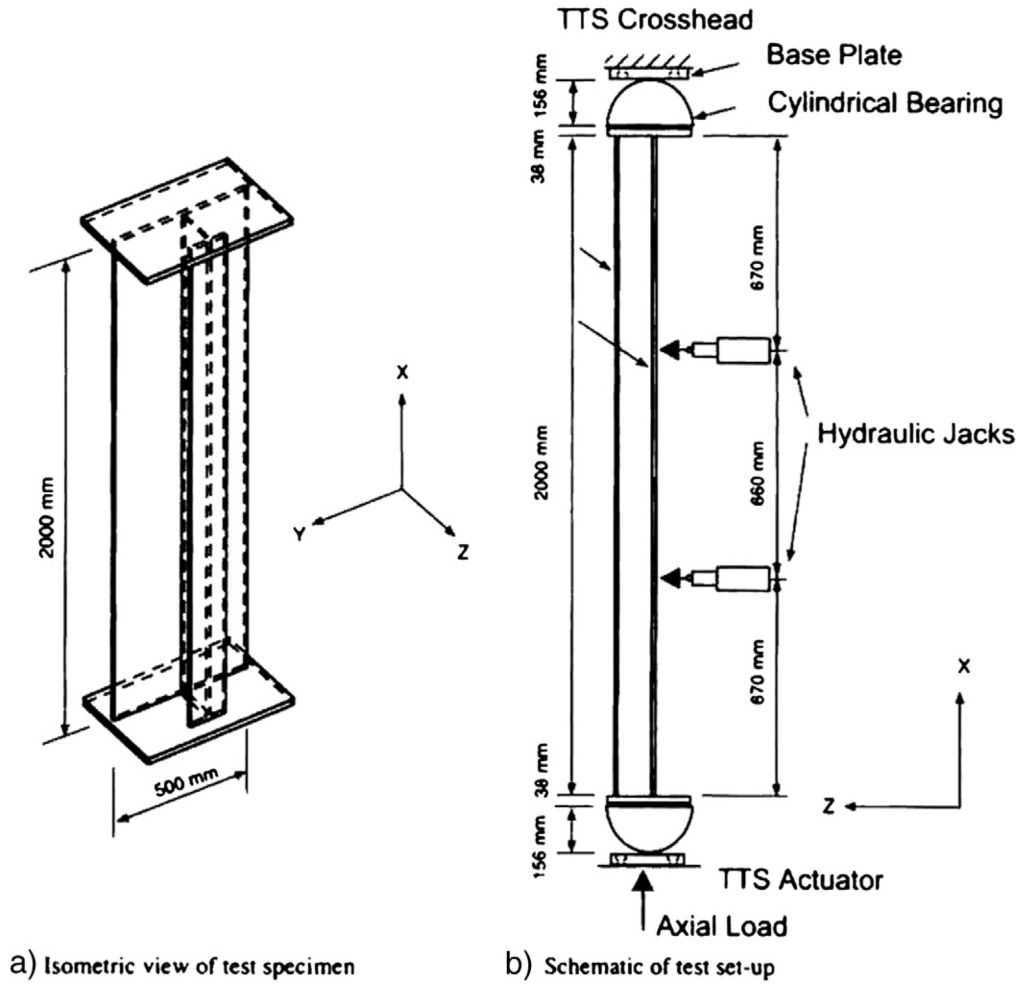

Fig. 2. Isometric view of the stiffened plate (left) and test arrangement (right). [8].

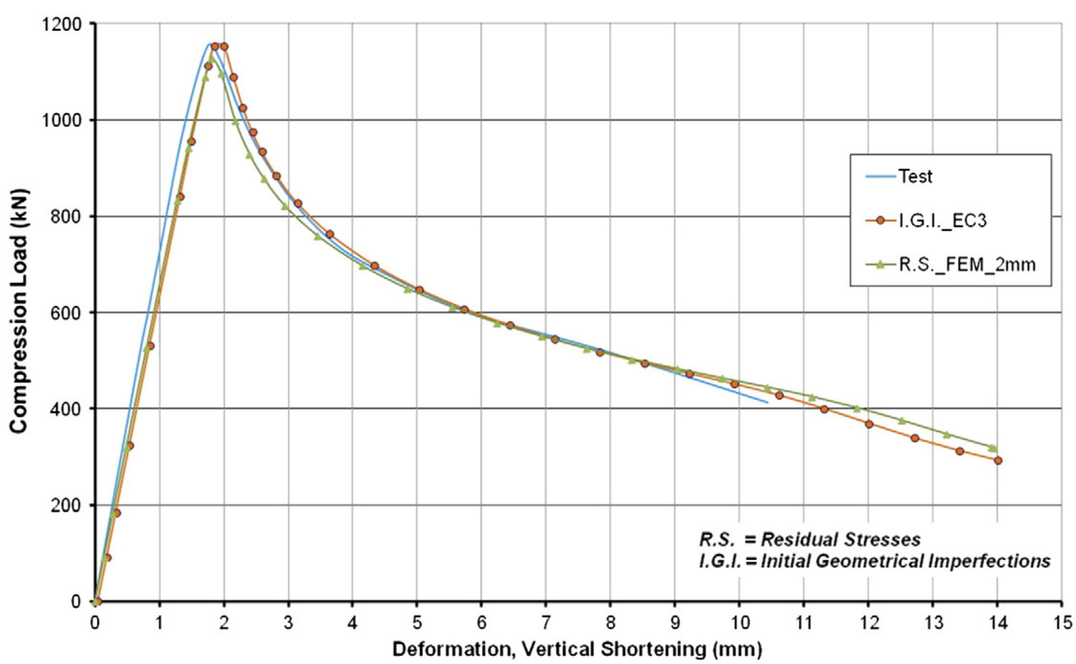

Fig. 3. Test results in comparison with FEM imperfections (I.G.I.) & residual stresses (R.S.).

Table 1
Recommendations for the consideration of geometrical imperfections and residual stresses in the verification of stiffened steel plates under compression and bending, susceptible to column-type buckling behaviour.

Imperfections	EN1993-1-5:2005 Annex C [3]		Proposed recommendations	
	Shape	Amplitude	Shape	Amplitude
Geometrical imperfections	Bow	Min (a/400, b/400)	Global buckling mode	a/400
Residual stresses	Assumed to be included in the equivalent geometrical imperfections	Assumed to be included in the equivalent geometrical imperfections	Rectangular patterns of membrane stresses	Tension: $+ f_y$ compression: $-0.30\ f_y$

[6]: "Execution of steel structures and aluminium structures — Part 2: Technical requirements for the execution of steel structures — Stage 34", the maximum permitted deviation of fabrication tolerances for stiffened plating is a/400, where "a" is the length.
2. The use of residual stresses in combination with measured initial imperfections yields lower ultimate load values than those given by models without similar initial geometrical imperfections. However, in the cases under study, the use of the failure shape without residual stresses provides results that are on the side of safety. Hence, a value of b/400 could be taken as an equivalent geometrical imperfection to consider both, geometrical imperfections and residual stresses.

It should be made quite clear that these recommendations were only validated through the referenced test and might not be appropriate for other types of loading, boundary conditions, and member slenderness. Besides, the following additional comments should be considered in the context of the previous recommendations:

1. Very good agreement was reached between the results of the FEM analysis and the experimental test.
2. Excellent agreement between the results of following the recommendations in Annex C of Eurocode 3 [3] and the proposed recommendations were reached.
3. With regard to initial equivalent imperfections: the use of equivalent imperfection shapes of similar amplitudes to maximum fabrication tolerances can produce acceptable results. It is important to provide information on test measured initial geometrical imperfections to obtain a good agreement between the FEM and the test results.
4. Buckling behaviour in "column-type" steel structural elements has been widely studied since the 1970s [10,11] and, more recently, through the buckling curves of Eurocode 3 [12]. However, the use of Eurocode buckling curves in steel-plated components subjected to compression with column-type behaviour could lead to very conservative results [13]. Plated box sections predominantly subjected to compression could be analyzed by FEM to obtain realistic results by using values of L/725 for the initial geometric imperfections.
5. With regard to residual stresses: it hardly appears necessary to introduce the exact pattern of real residual stresses in the model. Very good agreement is obtained with simplified stress distributions; although information on measured residual stresses in the specimen would be advantageous to achieve better accuracy.

3. Shear behaviour and bending interaction of stiffened and unstiffened welded girders

The recommendations in this section are drawn from the results of tests that formed part of the COMBRI project, conducted at the Institute of Steel Construction, RWTH Aachen, Germany. These tests on plated sections subjected to shear and bending stresses were reported in the following COMBRI project Technical Reports [4]: "Shear behaviour and bending interaction of stiffened and unstiffened welded girders", "Mid-Term, Technical Report № 3 (01/09/03-31/12/04)", and "Six-Monthly Technical Report № 4 (01/01/05-30/06/05)". The tests on two plated beams in the above-mentioned technical reports aimed to investigate shear behaviour and the interaction between shear and bending in the case of unstiffened and stiffened webs.

Fig. 4 depicts the specimens used in the parametric investigation, the results of which led to the recommendations on consideration of the initial imperfections.

The extreme cases were selected for the parametric test: 1 + a, long unstiffened beam and maximum bending moment, and 2 + b, short stiffened beam and maximum influence of shear stress [9].

"S3R/S4R shell" plate-type elements taken from the software library were used in the parametric analysis for the FEM calculations [2]. The transversal section of the plated beam was modelled with 8 elements in each flange and with 50 elements in the web. Over the longitudinal direction, the mesh was denser in the area of the web that was tested: for example, case 1 employed 125 columns of elements along the 2500 mm length of the beam. In relation to the boundary conditions, the load was considered to have been applied at a single node and the supports were modelled by a line of nodes, of the width of the flange.

Rather than a real reproduction of the geometric imperfections, a simplified approximation of the shape of the initial imperfection was proposed. In the parametric study, two alternatives were analyzed, the first mode of elastic bending and the one recommended in Annex C of Eurocode 3 [3].

With regard to residual stresses, given the approximation to the real distribution and the simplicity of the pattern advanced by Paik and Thayamballi [7], the rectangular stress pattern was applied in the subsequent parametric analysis, with traction amplitudes within a range of low, medium, and high values (0.80 f_y, 0.9 f_y and f_y, respectively). The values of compression stress varied between low, medium, and high values (0.05 f_y, 0.15 f_y and 0.30 f_y, respectively). The importance should be underlined of the residual stress pattern being in equilibrium, both in the model without deformation and in the deformed model, with the initial geometric imperfections. Calculation of the patterns in the model without deformation is easy [7]: the width of the zone under tension is as follows (1):

$$2 \times b \times t = b \times \sigma_{rc}/(\sigma_{rc} - \sigma_{rt}) \tag{1}$$

It is achieved for the zone under compression by establishing the stress equilibrium in the section, in such a way that no resultant of the residual stresses exists. Nevertheless, it is essential to point out that the introduction of the residual stress patterns in the deformed model, with the initial geometric imperfections, requires a preliminary step so that all the stresses in the section are in equilibrium, before any load is applied. This initial step consists of a preliminary calculation, without any load applied to the model, which allows a redistribution of the residual stresses and even modification of the initial deformation in the model [9], in order to guarantee an equilibrium stress state in the transversal section.

Having pointed out the above, 16 variants that consider initial imperfections were included in the parametric analysis (Table 2) and a plan was drawn up to gather information that would allow sufficient data to be offered in relation to three important questions: first, to note the influence of residual stresses in the stiffness and maximum load of the FEM; second, to establish a tolerance coefficient according to standard EN1090 [6] from which to obtain the initial geometric

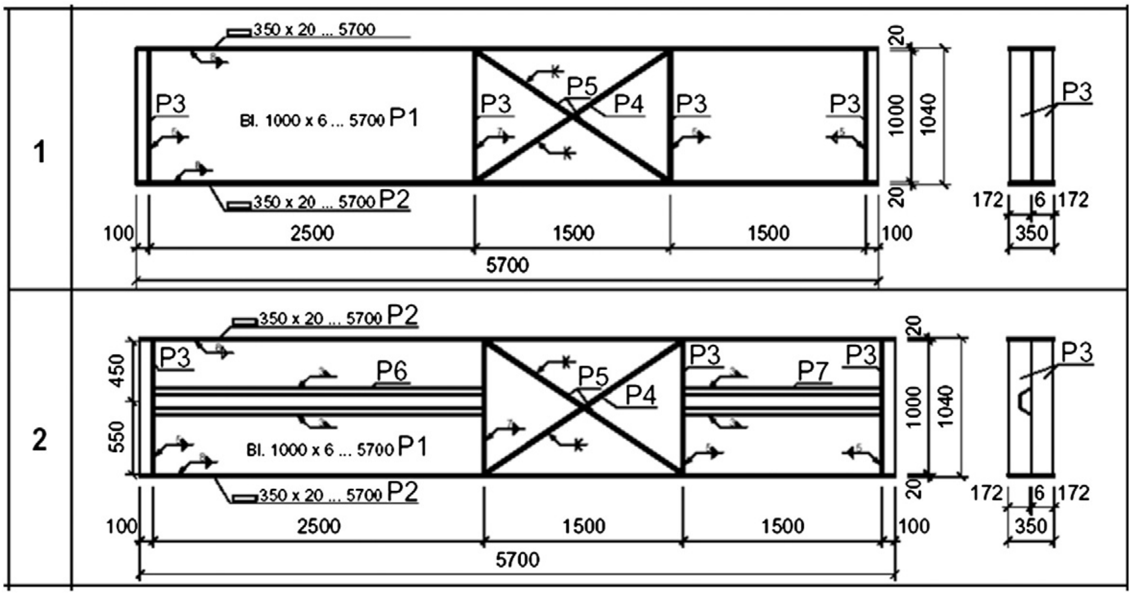

Fig. 4. Elevation views of: the unstiffened plated beam (case 1) and the stiffened beam with a longitudinal closed stiffener (case 2). [4].

imperfection amplitude for inclusion in the FEM; and, finally, to allow for the possibility of establishing equivalent geometric imperfection values as alternatives to those provided in Annex C of Eurocode 3 [3], so that the amplitudes provided by both sources may be multiplied by either reduction or amplification coefficients (0.5, 0.75, 1.0, 1.5 and 2.0).

So as to avoid a too lengthy or tedious explanation, it only includes cases (1 + a) and (2 + b) that are sufficiently representative in themselves, [9]. In the first place, the results of test (1 + a) on the unstiffened plated beam and the beam with a length of 2500 mm are discussed. Fig. 5 presents a comparison of the FEM load–deformation curves, without considering residual stresses, but with geometric imperfection amplitudes defined according to the Eurocode 3 standard on execution of structures. The amplitudes and the tolerances of the execution standard of steel structures both use the elastic bending mode to model the initial imperfection shapes. Both amplitudes generate curves that correctly fit the test curves and are in general safe.

Fig. 6 shows the influence of residual stress considerations on the previous results in comparison with the test curve.

Table 2
Parametric analysis considering the initial imperfections.

Case	Geometric imperfections		Residual stresses [7]
	Shape	Amplitude	
1	1st eigenmode	[EN1090-2:2004] (×1)	NO
2	1st eigenmode	[EN1090-2:2004] (×1)	Low effect
3	1st eigenmode	[EN1090-2:2004] (×1)	Medium effect
4	1st eigenmode	[EN1090-2:2004] (×1)	High effect
5	[EN1993-1-5:2006]	[EN1993-1-5:2006] (×1)	NO
6	[EN1993-1-5:2006]	[EN1993-1-5:2006] (×1)	Low effect
7	[EN1993-1-5:2006]	[EN1993-1-5:2006] (×1)	Medium effect
8	[EN1993-1-5:2006]	[EN1993-1-5:2006] (×1)	High effect
9	1st eigenmode	[EN1993-1-5:2006] (×0.5)	NO
10	1st eigenmode	[EN1993-1-5:2006] (×0.75)	NO
11	1st eigenmode	[EN1993-1-5:2006] (×1.5)	NO
12	1st eigenmode	[EN1993-1-5:2006] (×2.0)	NO
13	[EN1993-1-5:2006]	[EN1993-1-5:2006] (×0.5)	NO
14	[EN1993-1-5:2006]	[EN1993-1-5:2006] (×0.75)	NO
15	[EN1993-1-5:2006]	[EN1993-1-5:2006] (×1.5)	NO
16	[EN1993-1-5:2006]	[EN1993-1-5:2006] (×2.0)	NO

In both cases, a reduction occurs in the maximum load obtained by the model for the FEM calculation. It is more acute in the case of the execution standard for steel structures, with regard to both maximum load and the stiffness reduction of the model (note the curve with a less pronounced slope).

The use of a reduction coefficient of 0.50 and an amplification coefficient of 2.00, above the recommendations of the execution standard and Eurocode 3, provides minimum variations (case 9 versus case 13 and case 12 versus 16, respectively), as opposed to the cases in which they are not applied [9], as the effect is more important when the load increase coefficient is applied to the tolerances of the execution standard. Moreover, when residual stresses are considered, the results for maximum load are closer to those of the test, although the differences with the cases in which residual stresses were not used are very small.

Fig. 7 presents the failure modes for cases 5 and 12. Typical shear failure may be appreciated in the form of diagonal lines that reveal traction zones and web compression. The quality of the FEM is verified as it shows a failure mode that is identical to the one in experimental test.

In view of all the parametric analyses, it may be seen how the maximum load values that were experimentally obtained in test case (1 + a) [9] are very similar to those obtained by FEM, allowing us to affirm that the model is almost insensitive to variations in the amplitude of the initial imperfections or to the consideration or otherwise of residual stresses. The cases in which the recommendations of Annex C, Eurocode 3 [3] were applied are the closest to the experimental test results.

The results from the investigation of test case (2 + b) are qualitatively very similar to those reported for test case (1 + a) [9]. Therefore, the only point to mention is that the effect of the maximum allowable load and the stiffness of the model is greater at certain amplitudes of geometric imperfection, even though they remain insignificant (Fig. 8). The curves presented here show load curves versus model deformations with initial geometric imperfections, with no residual stresses, the amplitudes of which were calculated by the application of a reduction coefficient (0.50 or 0.75) or an amplification coefficient (1.50 or 2.00) above the recommendations of the execution standard and Eurocode 3.

The correlation with the test curve is correct up until the point of maximum load. It should be explained that the differences at the

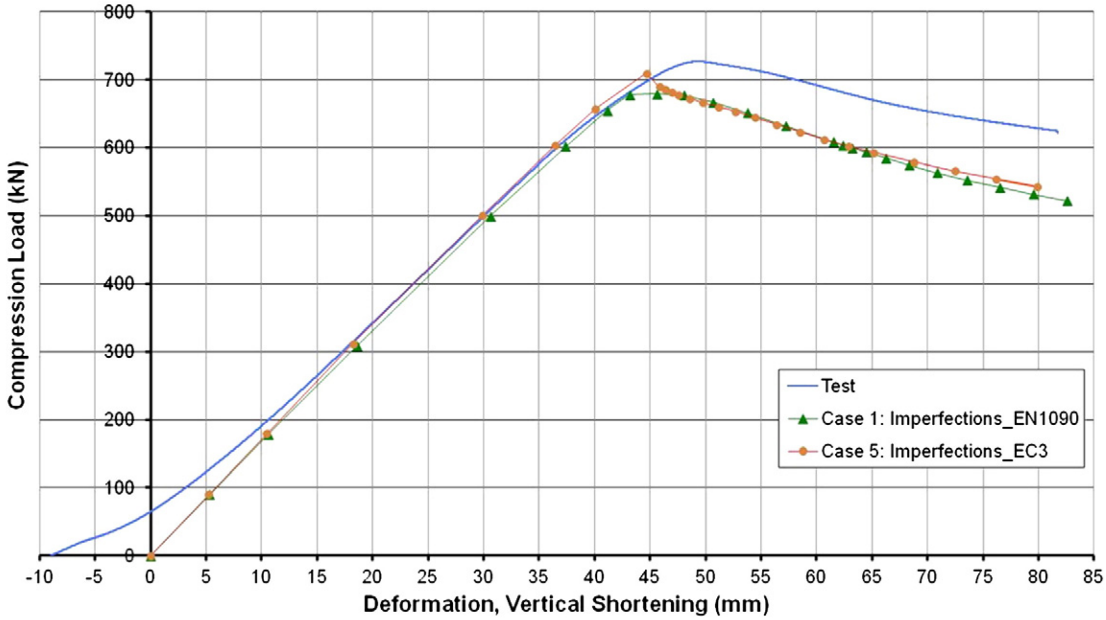

Fig. 5. Test (1 + a) and FEM in cases 1 and 5.

beginning of the test curve were due to the initial seating of the supports (not ideally rigid) when the loading process began. Once the beam stabilizes itself on the supports, the FEM shows a perfect fit with the test results until the ultimate load is reached.

The final conclusions drawn from this area of the research and the resulting recommendations are presented in Table 3. At this point, two main questions may be underlined:

1. Although the parametric study has proven that both the amplitude of the initial imperfections and the initial residual stresses have no effect on the results of the FE models based on the COMBRI project test results, the minimum values [6] from Annex L1 "Geometrical tolerances-Essential tolerances" are recommended, in which "a" is the smaller dimension of the plate, length, or depth.
2. The use of residual stresses in combination with measured initial imperfections gives lower ultimate load values than those given by models without similar initial geometrical imperfections. However, in the cases under study, the failure shape without residual stresses yielded results that were generally on the safe side. Therefore, a value of b/400 could be considered an equivalent geometrical imperfection for the consideration of both geometrical imperfections and residual stresses.

It should be carefully noted that these recommendations were only validated in the above-mentioned test. They might not therefore

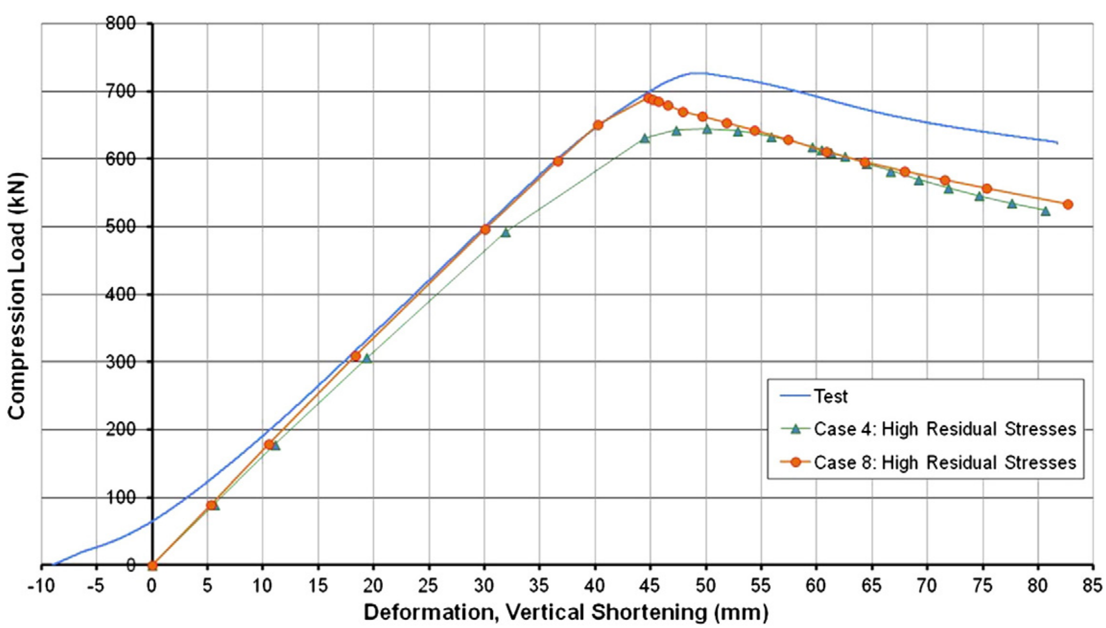

Fig. 6. Test (1 + a) and FEM in cases 4 and 8.

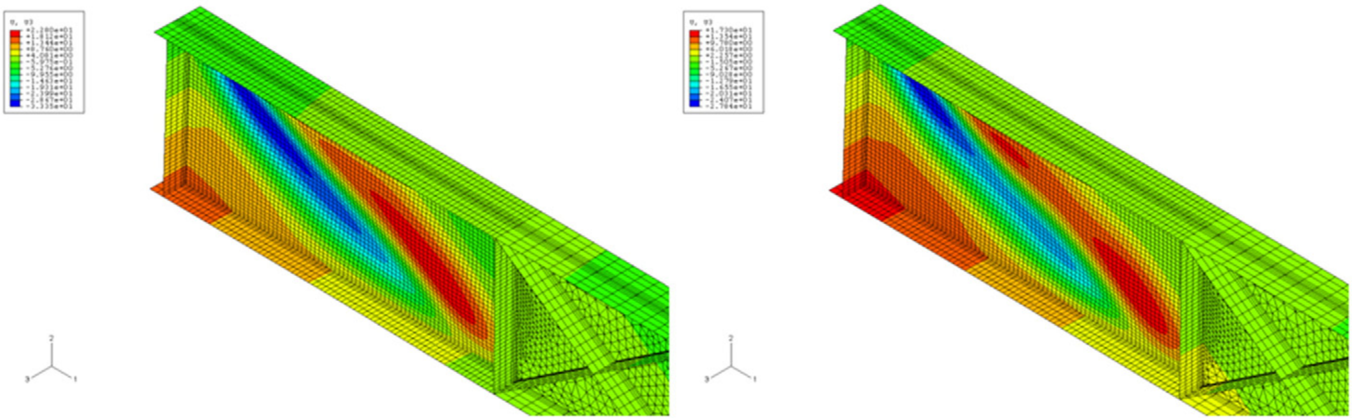

Fig. 7. FEM failure modes for case 4 (left) and case 12 (right).

be appropriate for other types of loading, boundary conditions, member slenderness, etc. Besides, the following additional comments should be considered in the context of previous recommendations:

1. Good agreement was obtained for both peak load values and failure modes [4].
2. Very good agreement between the results obtained following *Annex* C of Eurocode 3 [3] recommendations and the proposed recommendations were obtained.
3. With regard to the initial equivalent imperfection, the different values from the relevant execution standard, EN1090 [6] and from *Annex C* of Eurocode 3 [3], which have a bearing on their amplification and reduction coefficients, have no effect on the results of the FEM in the COMBRI project tests.

This "*lack of sensitivity*" of the beams subjected to shear stress was detected by other researchers participating in the COMBRI project [14–16]. Their conclusion was that an initial geometric imperfection of a/800 could be considered suitable to obtain a realistic result. Moreover, selection of the initial imperfection shape is considered more relevant than the initial amplitude in the referenced works, in order to obtain realistic results for failure shape and peak load.

In the case of residual stresses, the influence of the residual stress amplitudes on stiffness and ultimate load do not affect the results obtained in the FE models based on the COMBRI project test results.

4. I-Section plated girder subject to patch loading

The recommendations presented in this section are based on the tests conducted at the Division of Steel Structures, Luleå University of Technology, Sweden, on plated beams subject to patch loading, based on the tests described in several Technical Reports of the COMBRI project [4,17]. These technical reports investigated the patch loading behaviour of several plated beams, examining three patch load lengths: 200 mm (P200), 700 mm (P700) and 1400 mm (P1400), (modifying their respective loading mechanisms by means of one, two and four blocks). Fig. 9 shows the specimens used in the parametric investigation that led to the recommendations for the consideration of their initial imperfections.

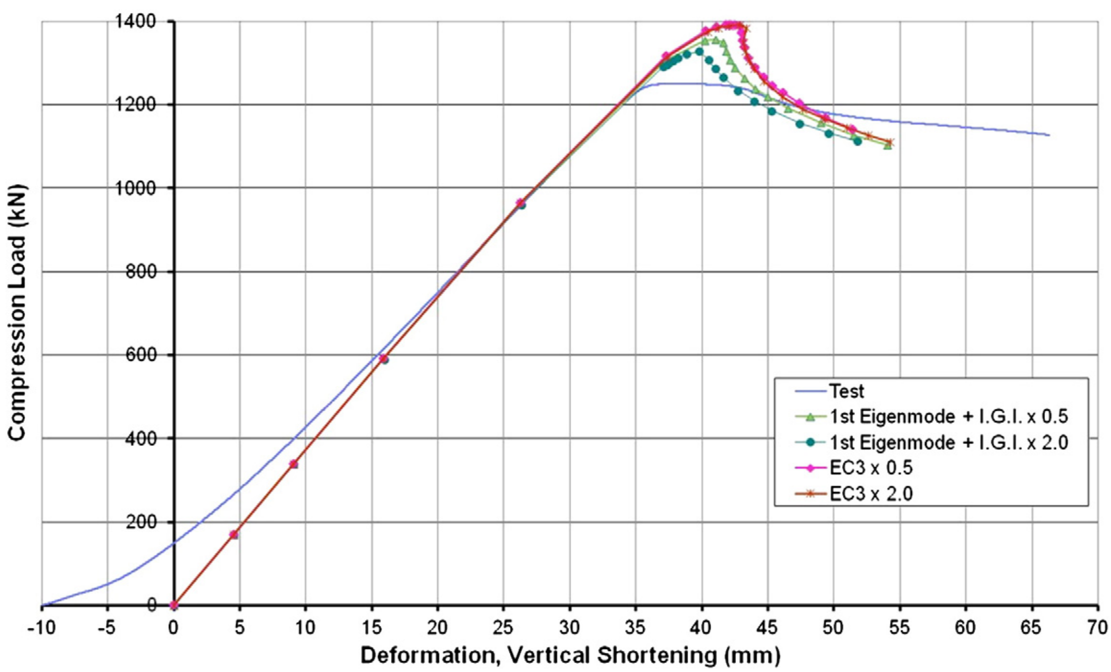

Fig. 8. Test (2 + b) and FEM in cases 9, 12, 13 and 16.

Table 3
Recommendations for the consideration of geometrical imperfections and residual stresses, for the analysis of shear behaviour and bending interaction of stiffened and unstiffened plated girders.

Imperfections	EN1993-1-5:2005 Annex C [3]		Proposed recommendations	
	Shape	Amplitude	Shape	Amplitude
Geometrical imperfections	Buckling shape	Min (a/200, b/200)	Local, at plate level buckling mode	a/400
Residual stresses	Assumed to be included in the equivalent geometrical imperfections	Assumed to be included in the equivalent geometrical imperfections	Rectangular patterns of membrane stresses	Tension: +0.80 f_y Compr.:-0.05 f_y

The beams in the test were made of S355 steel plate, supplied with a 6 mm web gauge and a 20 mm flange [9]. The influence of plate thickness and its possible anisothropy was evaluated in tensile tests [17] (specimens extracted from the transversal and rolling direction). Slight anisothropy was noted in both plates, with greater elasticity for the 6 mm gauge plate (hardened by rolling) and greater ultimate elongation for the 20 mm plate. The steel plate was incorporated in the beams in such a way so that the rolling direction coincided with the longitudinal direction of the beam in the flanges and with the vertical direction in the web.

No measurements were taken for the tests to which this study refers, in order to determine the residual stresses produced in the beam manufacturing process. The parametric analysis is therefore also based on certain residual stress criteria [7], so as to determine the maximum traction and compression stresses, together with the respective areas that are affected.

In addition, the initial geometric imperfections of the web had been measured before the tests were conducted, resulting in a maximum imperfection value of 1.6 mm (0.27 times the thickness of the web), in the form of an arc. This is a very small imperfection (approximately h/4.444), the maximum threshold being [6] $\Delta = b/100$ provided that $\Delta \geq t_f$, where b is the side of the web and t_f is its thickness.

In the case of the beam used for the P700 test, the initial imperfection measured on the web at the height of the horizontal in-load plane reached a maximum value of 1.07 times the gauge of the web (6.4 mm), which approximately corresponds to the recommendation for initial equivalent geometric imperfection [3]; in other words, h/200.

Beam P1400 registered a maximum value of 0.62 times the gauge of the web (3.7 mm), as in the case of beam P200, which is below the specifications in the relevant execution standard and Eurocodes, in all cases the imperfections being in the form of an arc [17].

Although the parametric studies were developed on the basis of the three aforementioned tests, the load application of 200 mm was of greatest interest [9], due to its very localized failure mode that was sensitive to the initial imperfections, which occurred because of plastification of an area of the web close to the upper flange. The failure mode in cases P700 and P1400 was buckling (instability of the web) which, especially in the second case (similarity with column-type failure rather than plate failure), was more global and less dependent on the initial imperfections. The initial geometric imperfection that was introduced in the area closest to the in-load application point is therefore of great relevance.

A comparative (benchmarking) study, based on information provided by an earlier study on S460 steel in plated beams [18], which also referred to concentrated loads, was conducted with a view to obtaining preliminary confirmation of the best modelling strategy. The purpose of this comparative process was to select the most suitable mesh density and, in second place, the correct method of modelling the system for the introduction of concentrated load. The conclusions of the benchmarking study were included in the parametric analysis (Table 4), with the result that the geometric imperfection values under consideration were in the range of those in Table C2 and Figure C1 of Annex C of Eurocode 3 [3], as well as lower values to include the effect of residual stress; specifically, in reference to the tolerances in the standard for the execution of steel structures [6].

In reference to the first question (mesh density), it was determined [9] that the most suitable mesh should contain 2900 elements with 8 along the flanges and 38 at the height of the web. This was done with S4 Abaqus-type elements [2], with plate-type elements (Shell) characterized by the formulation of shear flexible plates, according to the Mindlin–Reissner theory, which are recommended because of their adaptation to both slender and thick gauge plates, their computational efficiency, insensitivity to distortion, and because of their capability to assume finite deformations.

As regards the second question (modelling of the load), a series of blocks or cylinders [9] were used in the tests as a means of applying load. Satisfactory results were obtained, after several simulations, when the model was prepared for use in the FEM software, by using lines of nodes at the load application points of the upper flange.

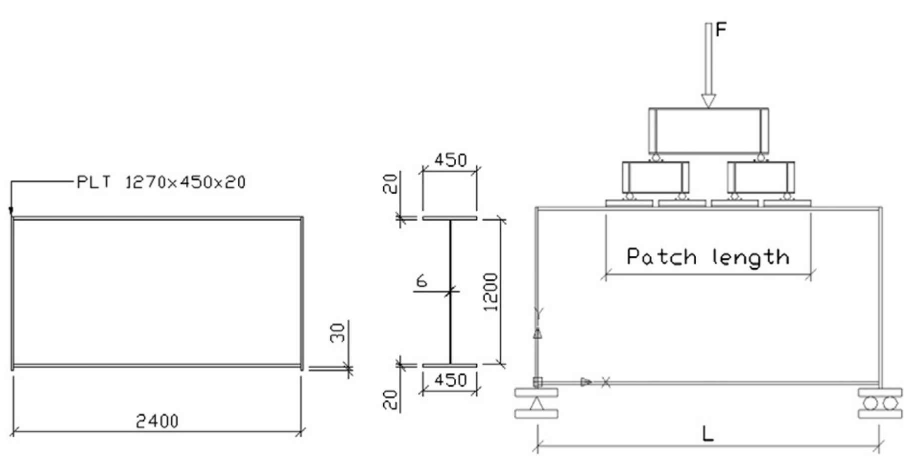

Fig. 9. Specimens for patch loading (left) and test configuration (right) [4,17].

Table 4
Design of the parametric analysis for the consideration of initial imperfections [4].

Case	Geometric imperfections		Residual stresses
	Shape	Amplitude	
1	Annex C, EC3, Parts 1-5	Annex C, EC3, Parts 1-5	NO
2	1st eigenmode	EN1090-2	Low effect
3	1st eigenmode	EN1090-2	Medium effect
4	1st eigenmode	EN1090-2	High effect
5	1st eigenmode	Coef. tolerance, EN1090-2	NO
6	Failure shape analysis	EN1090-2	Low effect
7	Failure shape analysis	EN1090-2	Medium effect
8	Failure shape analysis	EN1090-2	High effect
9	Failure shape analysis	Coef. tolerance, EN1090-2	NO

With regard to the failure shape, in the case of the shortest length of application (P200), the failure was more localized, as previously indicated, and occurred due to plastification of the area of the web closest to the upper flange, in such a way that buckling failure (instability of the web) rather than plastification occurred in cases P700 and P1400 and the failure shape of P1400 was closer to column-type rather than plate-type failure.

This investigation aims to provide general recommendations that are not restricted to beams with a small degree of initial imperfections. It is therefore essential to evaluate the sensitivity of the initial imperfections to concentrated loads. With that objective in mind, a large number of simulations were conducted with type S460 steel [9], in order to investigate variations in ultimate load values and failure shapes.

Following the above line of reasoning, a simplified approximation rather than a real reproduction of the geometric imperfections is proposed for the shape of the initial imperfection, studying the shape that corresponded to the first bending mode and a shape corresponding to the predicted failure mode, referred to as its "failure shape".

The introduction of the residual stress pattern in the deformed model (once the initial geometric imperfections are included), requires a preliminary step (before any load is applied) so that all the stresses present in the section are in equilibrium, in accordance with the following key points [9]:

1. Calculation of the bending modes of the structural component for a particular case of load and selection of the first bending mode or failure shape.
2. Introduction of the initial geometric imperfection amplitude, first eigenmode, and a combination of buckling modes or failure shapes. No stress is introduced in the model in this step.
3. Introduction of the ideal residual stress pattern in the deformed model.
4. Balancing of the ideal residual stress patterns in the deformed model.
5. Deformation load analysis and final result.

It is the fourth step which should be treated with special care, given that it can produce important modifications in the deformation that is initially included in the model, in relation not only to its amplitude but also to its shape. The benchmark analysis presented a deformation in the phase that balanced the residual stress pattern in the deformed model, which is the result of sinusoidal residual stresses in three waves, when the predicted bending mode and the failure mode consisted of a single wave in the web.

In short, a change in the initial imperfection shape took place, which did not coincide with the predicted failure shape, and which produced variations in the maximum amplitude of the initial geometric imperfection, the impact of which was stronger at lower geometric imperfection values. In addition to the effects, it is important to highlight how a variation in the localization of the point of maximum amplitude of the geometric deformation also occurred in the case of this load. As an example, it may be pointed out that [9], the vertical distance (after balancing the residual stresses) of the point of maximum lateral displacement for an initial imperfection with a maximum amplitude of 3.00 mm, over the axis of symmetry is 65.47 mm, which is transformed into +108.93 mm, for a maximum amplitude imperfection of 30.00 mm.

Table 4 presents the combination of cases for the proposed parametric analysis, the aim of which was to group together sufficient results to establish recommendations on the consideration of geometric imperfections and residual stresses.

On the basis of earlier studies [9], particularly the case of P200 because of its relevance, the choice of failure shape for the initial geometric imperfection may be said to have a clear effect on the model. It is less rigid owing to the buckling mode that is practically symmetrical with regard to the axis of vertical symmetry of the beam web. On the contrary, "the failure shape" situates the point of greatest displacement with regard to the perpendicular plane of the web closer to the upper flange. This effect was previously mentioned in reference to variations in the localization of the point of maximum amplitude of the initial geometric deformation.

It has been noted that the effect caused by the consideration or otherwise of the residual stresses is identical to the case in which the first eigenmode is used as a shape of the initial geometric imperfection, obtaining a good analytical-experimental fit with error values of between 1% and 4%, with regard to the ultimate load value obtained in the test, which is a safe margin.

In relation to the cases in Table 4, Fig. 10 (considering nominal steel values) presents the deformations in the ultimate load of the transversal section of the web under the load application point; the x-axis corresponds to the initial transversal deformation in relation to the thickness and the y-axis to the upper part of the web with the origin in the lower flange (mm).

Notwithstanding the above, a model may also be constructed from the tension tests [17], with the real values of the steel (S355) that was used, as may be appreciated in Fig. 11, where label P200 corresponds to the experimental curve, and labels b/100 to b/800 correspond to the initial geometric amplitude imperfections ("b" is the panel height, or the side of the web).

As was the case with the modelling of the material according to the nominal values, in this case, the fact that "the failure shape" was used for the initial geometric imperfections gave rise to a less rigid model. Having analyzed the maximum (or ultimate) load values, it was noted that the selection of a series of representative cases from the set of simulations, produced a satisfactory maximum load obtained by FEM in all cases, with an error of below 10% with respect to the test. Furthermore, in relation to the results that are closest to the experimental test, a clear influence of the value of the initial amplitude over the ultimate load in the models is notable. In the P200 test, the measured real imperfection of which is very small, it may be seen how small increases in the amplitude of the initial imperfection lead to a drop in the ultimate load.

With regard to the effects of a general scope, it may be affirmed that the use of a similar initial imperfection shape leads to more conservative results than in the case of using the shape of the first eigenmode. Equally, the inclusion of residual stresses always leads to a reduction of the ultimate load that is obtained, taking the necessary precautions to avoid possible undesired effects due to interaction with the initial deformation of the model.

Moreover, with regard to the results in which the failure mode was used with different coefficient correctors (on maximum fabrication tolerances, permitted by the standard [6]), the possibility of establishing some equivalent geometric imperfections was considered viable, based on the tolerances of structural manufacturing techniques and modified by coefficients, other than those now found in Annex C of Eurocode 3 [3], that would respond to the predicted degree of imperfection.

The final conclusions, of this area of research and the accompanying recommendations are presented in Table 5. Two main points of discussion may be stated here:

1. Although the parametric study has achieved proven results with amplitudes of between b/100 and b/800, close to the test load

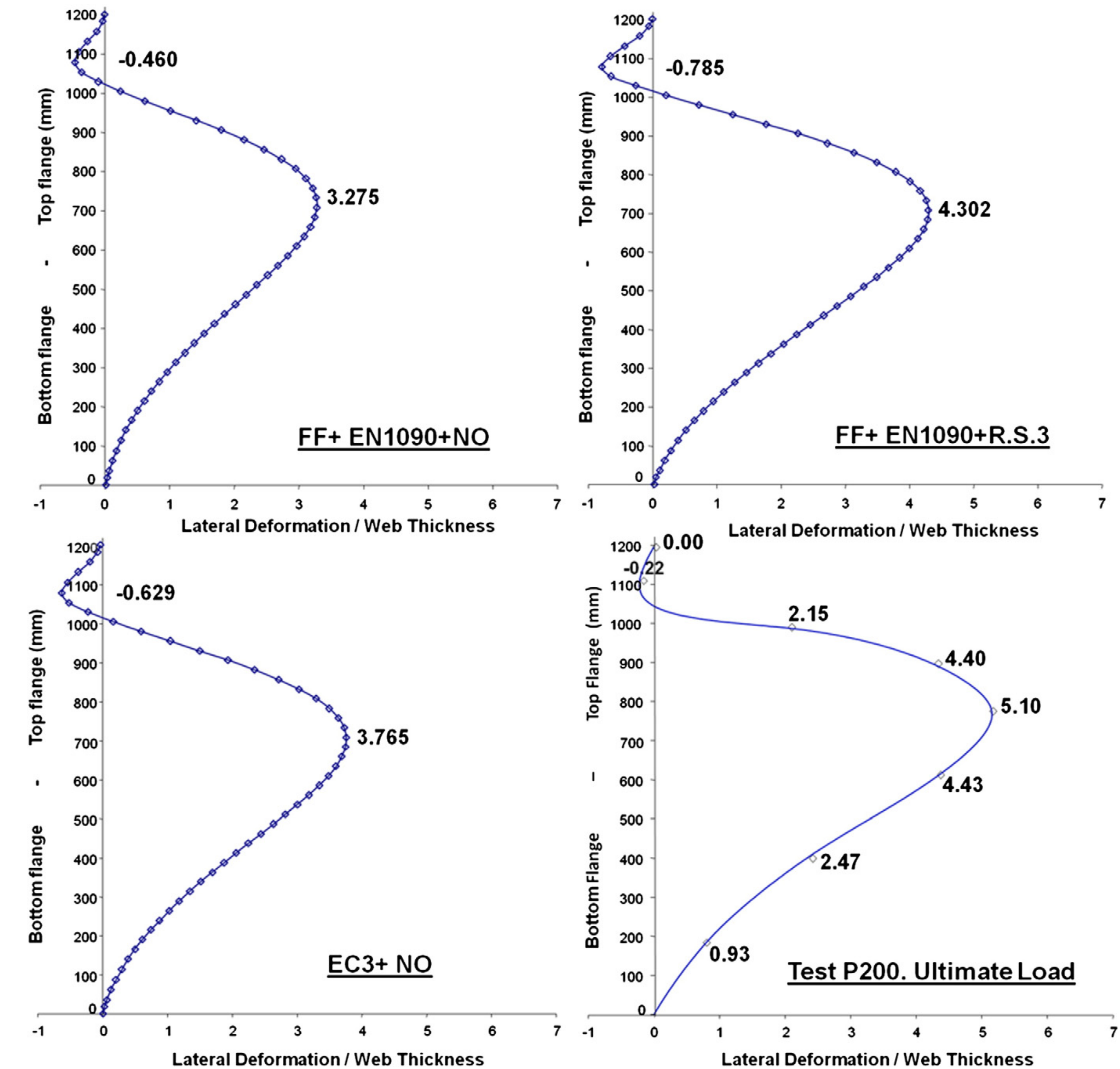

Fig. 10. Transverse deformations of web plate at maximum load. Parametric analysis in cases 9 (upper-left), 8 (upper-right) and 1 (lower-left) and P200 test (lower-right). EN1090: amplitudes (EN1090-2:2004) [6]; EC3: amplitudes (EN1993-1-5:2005) [3]. FF: "failure shape" (Preliminary FEM analysis) and amplitudes as per EN1090 [6]. R.S.3: Residual stresses with high degree of effect; NO: without residual stresses.

displacement curve, the model of I - section plated girders subject to patch loading has an important sensitivity to amplitudes of geometrical and residual stresses, hence the recommendation to use the value of the maximum fabrication tolerances given by the *Annex L1* "Geometrical tolerances-Essential tolerances" of the *EN1090-2:2004* [6]*:* "Technical requirements for the execution of steel structures-Stage 34", where "b" is the dimension of the plate corresponding to the depth of the plated beam.
2. The use of residual stresses in combination with measured initial imperfections yielded lower ultimate load values than those given by models without similar initial geometrical imperfections. However, in the cases under study, the use of the failure shape without residual stresses yielded safe results. Hence, a value of b/400, or b/100 for sections on bridge supports, could be considered a geometrical imperfection equivalent to the consideration of both geometrical imperfections and residual stresses.

It should be carefully noted that these recommendations were only validated through the referenced test and might not be appropriate for other types of loading, boundary conditions and member slenderness. Besides, the following additional comments should be considered in the context of previous recommendations:

1. Very good agreement was obtained for both peak load values and failure modes between the results of the FEA and the test results.
2. With regard to initial imperfections, it appears acceptable to introduce an equivalent initial imperfection, which comprises the

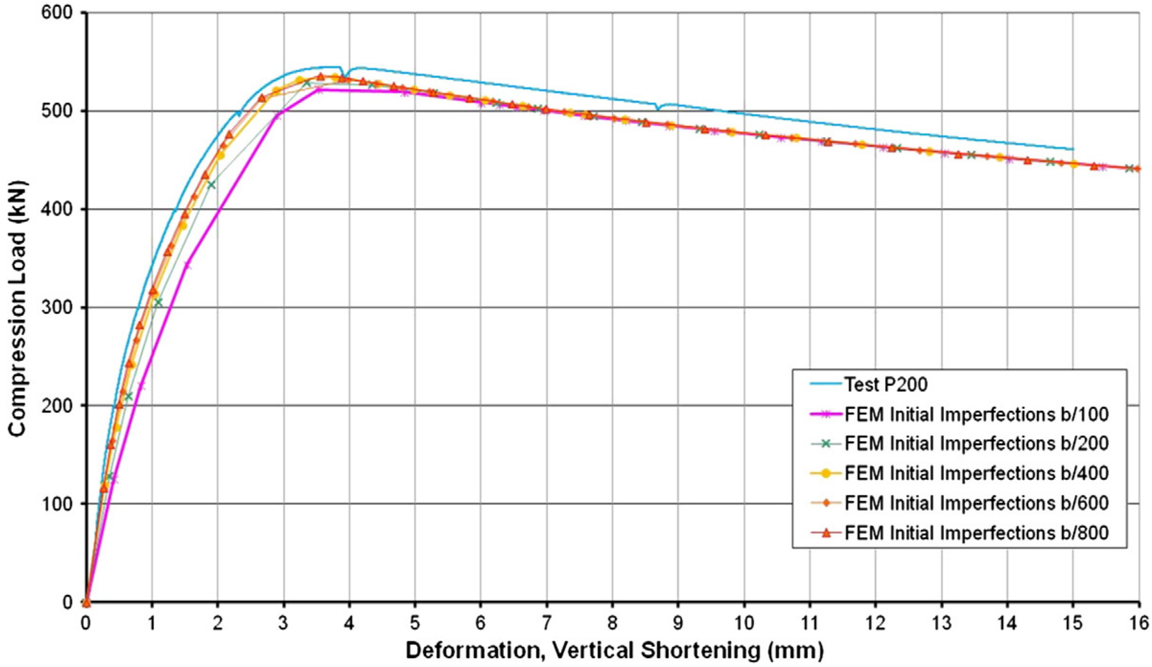

Fig. 11. P200 load–deformation test versus parametric study considering imperfections according to the first eigenmode and without residual stresses.

fabrication and the welding imperfections. The use of equivalent imperfection shapes of similar amplitude to the maximum fabrication tolerances can produce acceptable results.

- The FEM clearly shows the influence of the imperfection amplitude on the ultimate load.
- The use of the failure shape (collapse-affine shape), for the imperfections, in the FEM leads to lower ultimate load values than those given by eigenmodes.

3. With regard to residual stresses, it hardly appears necessary to introduce the exact real pattern of residual stresses in the model. Very good agreement is obtained with simplified stress distributions. A high level of residual stresses provides good results for the test. Residual stresses in combination with measured initial imperfections yield lower ultimate load values than those given by models without similar initial geometrical imperfections.

In order to support the observed sensitivity of the patch loading case, it is important to take into account the following considerations from other researchers who have studied the impact of initial imperfections in plated sections.

- The weakening effect of these initial imperfections (geometrical and residual stresses) is most pronounced in the range of intermediate slenderness: i.e. slenderness at which the critical buckling stress and the yield stress are roughly equal [19].
- Strength knockdown is most accentuated for plates of intermediate slenderness subject to compressive stressing and is least pronounced for shear loaded cases, while it is practically negligible for rectangular plates under pure shear [20].
- In beams with longitudinal stiffeners, it is not possible to neglect the effect of initial imperfections. According to Davaine et al. [21], it is possible to obtain, with the same model, a range of variations in the peak load obtained by FEM from −2.30% to +24.00% with respect to the test result, depending on the initial imperfections taken into consideration.
- The impact of the shape and amplitude of the initial geometric imperfections in hybrid girders on FEM results according to Chacón et al. [22–25] can lead to differences in the peak load of 10%, in the case of large distances between transversal stiffeners.

5. Conclusions

The results of the research presented in this paper have focussed on three typical application cases of steel plated beam elements for bridges. These results have pointed to some general conclusions for the consideration of imperfections for the design based on Finite Element Methods of steel plates which are subjected to in-plane forces in plated structural elements of bridges.

First of all, it may be affirmed that the FEM provides very good agreement between the models and the experimental test results used for their validation.

Regarding the consideration of initial imperfections, the recommendations of *Annex C* of *Eurocode 3 Parts 1–5*, (CEN, 2006), provide good results, in general. However, the recommendations taken from Tables 1, 3 and 5 in relation to the cases presented in this paper could lead to more accurate results, closer to the experimental test

Table 5
Recommendations for consideration of geometrical imperfections and residual stresses, for the verification of I-section plated girders subject to patch loading, susceptible to plate-type buckling behaviour.

Imperfections	EN1993-1-5:2005 Annex C [3]		Proposed recommendations	
	Shape	Amplitude	Shape	Amplitude
Geometrical imperfections	Buckling shape	Min (a/200, b/200)	Local, at panel level failure shape	b/400 (b/100, sections on supports)
Residual stresses	Assumed to be included in the equivalent geometrical imperfections	Assumed to be included in the equivalent geometrical imperfections	Rectangular patterns of membrane stresses	Tension: $+f_y$ Compression: $-0.30 \cdot f_y$

results used for their validation. This is especially applicable to the case of plated beams subjected to patch loading.

Patch loading in plated beams is very sensitive to initial imperfections; e.g. if small initial magnitudes are used, the results will be less than conservative for the prediction of the peak loads of the test. Thus, the use of imperfection shapes based on the expected failure shape and amplitudes in the range of the fabrication tolerances is recommended.

It has been observed that the impact of initial geometric imperfections on the reduction of the peak load provided by the FEM is very important, in the case of plated beams subjected to patch loading. In contrast, it is almost negligible in the case of plated beams subjected to pure shear stress.

It is not necessary to use initial residual stress in the FEM stress patterns based on real measured residual stresses. The results obtained with the proposed simplified rectangular pattern used in this paper, based on a rectangular distribution of membrane stresses, are in good agreement with the test results.

In all the cases presented in this paper and in all the parametric studies in support of the recommendations, the use of initial residual stresses combined with initial geometric imperfections in the FEM has led to smaller peak load values than in the models with the same initial geometric imperfections, but with no consideration of initial residual stresses.

Finally, the adoption of initial equivalent geometric imperfections to consider both geometric imperfections and residual stresses is considered an acceptable option. However it is possible to offer alternative values to those currently available in *Annex C* of *Eurocode 3 Parts 1–5* (CEN, 2006), by means of an adequate calibration that would take into account both fabrication tolerances and residual stresses resulting from welding works.

This paper has offered a preliminary approach, but further research is still required on the implications of its recommendations, to enlarge their scope of application to cover a wider range of slenderness, stiffening, and types of plated steel elements.

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