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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.

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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.

- *Geometric 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

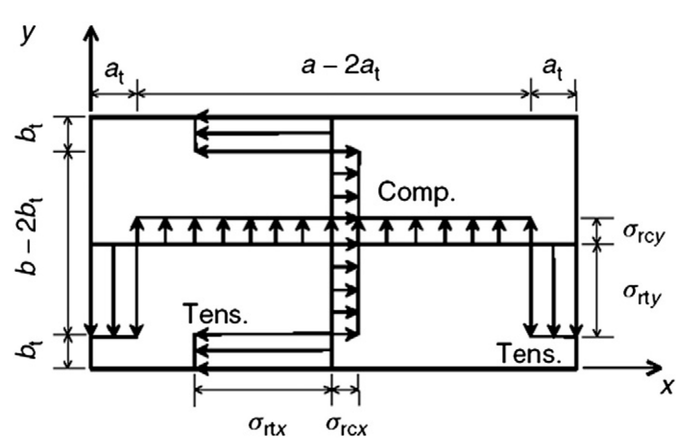

Fig. 1. Simplified patterns of residual stresses based on a rectangular distribution of membrane stresses. [7].

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