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THE INTERACTION BEHAVIOUR OF STEEL PLATES UNDER TRANSVERSE LOADING, BENDING MOMENT AND SHEAR FORCE

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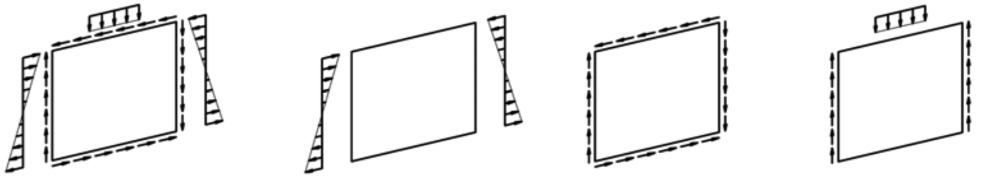
***Abstract**. This paper focuses on the design of steel plated girders under combinations of transverse loading, bending moment and shear force. In the member states of the European Union the design of slender steel plates is covered by EN 1993-1-5:2006. Although conclusions from literature show a rather significant interaction between transverse loading and shear force (F-V), no consideration of this type of interaction is made in Section 7.2 of EN 1993-1-5:2006. In order to close that gap experimental and numerical studies were undertaken to analyse the stability behaviour and to identify the influence of key parameters. Based on that an F-V proposal is developed which is completed by the consideration of a bending moment so that finally a fully usable F-M-V interaction equation is proposed.*

1 INTRODUCTION

Steel plated structures occur as part of slender structural systems due to their advantageous strength-to-weight ratio which allows especially aesthetical solutions. Transverse stiffeners are usually provided at locations where forces are applied locally. However, this is not possible if the position of the load introduction is transient e.g. in case of bridge girders being incrementally launched or for deep crane runway beams. In both cases high transverse forces have to be introduced into the slender steel webs of the girder, often with high bending moment and shear force at the same time, see figure 1.

Although conclusions from literature show a rather significant interaction between transverse loading and shear force (F-V), no consideration of this type of interaction is made in Section 7.2 of EN 1993-1-5 [1]. In order to close that gap experimental and numerical studies were undertaken to analyse the stability behaviour and to identify the influence of key parameters. Based on that an F-V proposal is developed which is completed by the consideration of a bending moment so that finally a fully usable F-M-V interaction equation is proposed.

Before current proposals are evaluated and improvements are proposed, considerations on the general formulation of an interaction equation and on the choice of the verification point are presented in the following sections.



a) combined loading b) longitudinal stresses c) shear stresses d) transverse stresses

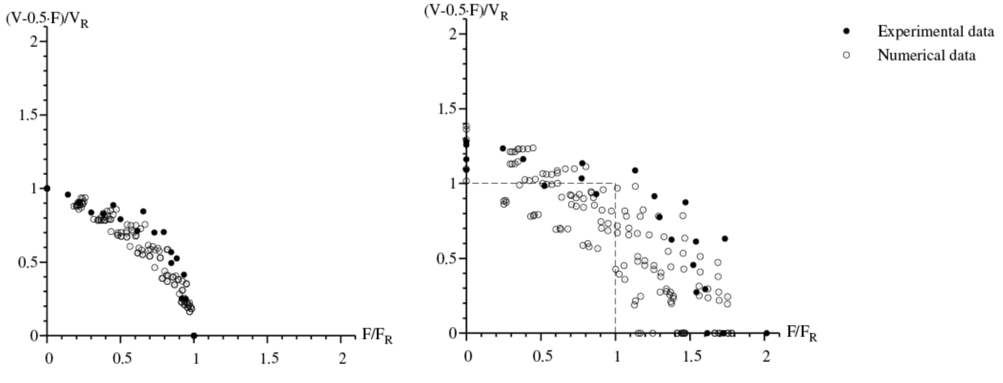
Figure 1: Load combinations of a transversely loaded panel.

2 ON THE GENERAL FORMULATION OF AN INTERACTION EQUATION

In addition to a development of a design method for a single load case, the formulation of an interaction equation puts additional difficulties which are:

- **Limited number of available data.** In general, there is only a limited number of available data points particularly from experiments because the ratio of loading is added as an important parameter so that in order to be able to identify the parameter variation within a given load ratio a similarly large number of specimens should be tested than for a basic load scenario.
- **Reference value for basic loading.** The reference strength for basic loading coming from resistance models usually has a variation itself. The interaction equation can therefore only be as good as the resistance model for the reference strength. It is desirable to know the experimental ultimate load from basic loading for each interaction test series, otherwise an assumption based on a resistance model has to be made.

In the following, the interaction between transverse loading and shear force is exemplarily used to illustrate the aforementioned difficulties and to explain the decisions which were taken in the formulation of the proposals later on. Figure 2a) shows the F-V interaction with reference strengths based on basic loadings from experimental and numerical studies in which nothing else than the load parameter was varied in comparison to the interaction case. In contrast to this figure 2b) shows the same interaction data but with reference strengths according to EN resistances. It can be shown that the data increasingly scatters for the EN reference strengths due to the variation of the design model itself. In order to draw a concise conclusion on the interaction behaviour, it would be necessary to eliminate the effect of the reference strength's design model. In the F-V study, this was done while studying the effect of parameters where experimental and numerical reference strengths are also referenced. Thus we can state that a procedure similar to figure 2a) is better suited to analyse the interaction behaviour.



a) experimental and numerical reference strengths

b) EN reference strengths

Figure 2: Evaluation of interaction data with F_R and V_R according to experimental and numerical reference strengths.

Besides that the quality of the reference strength influences the interaction data, so it is not the best way to evaluate or define an interaction equation based on design models for reference strengths. Imagine that only the experimental data would be available in figure 2b). In that case only two data points lie in the quadrant which is relevant for interaction and the interaction equation would be less strict than in the case when the numerical data are additionally considered. The parameters of the experiments are covered rather by the means and upper fractiles of the resistance models which would lead to an underestimation of interaction. It can be shown that if parameters are chosen such that they cover the lower tail of the resistance models variation, as done in the numerical simulation, interaction becomes more severe. Of course, if the definition of interaction equations is coupled to application ranges which restrict the use e.g. to the parameters of the experiments, interaction may be defined more loose. However, in view of general applicability and safety, the reference strengths should be based on corresponding experimental and numerical basic loadings whenever possible.

3 ON THE CHOICE OF A VERIFICATION POINT

A plate is usually not subjected to constant stresses but rather to stress gradients. Focusing on the resistance to transverse loading, it is presumed that the worst case is when the patch loading is placed at the centerline of the plate. At this location also the bending stress induced by the transverse loading becomes extremal. For the interaction between transverse loading and shear force, however, there are basically two choices which reference load can be assigned to each axis of an interaction diagram:

- The applied patch load F is related to the pure patch loading resistance F_R and the maximum internal shear force $V_{int,max}$ is related to the pure shear resistance V_R.
- The applied patch load F is related to the pure patch loading resistance F_R and the applied shear force is corrected by 0.5-times of the applied patch load.

Although the maximum value of the internal shear force can be easily attained from the distribution of internal forces, its use turned out to be disadvantageous in an interaction diagram because the verification of the pure patch loading resistance already includes the shear force (=0.5·F) which is induced by the patch load.

The second approach subdivides the combined loading into the two basic load cases "transverse loading" and " shear force" which can be composed to create one load combination. Thus, the influence of shear stresses which are caused by the transverse loading can be better accounted for. Then the verification point coincides with the one for bending moment. For these reasons the verification point at the centerline of the transverse loading, i.e. at maximum bending moment and average shear, is taken.

4 EVALUATION OF THE INTERACTION EQUATIONS

The reference strengths are important parameters and a lot of progress has been made for patch load resistance models as summarised in [2]. Therefore an evaluation of the interaction equations is performed not only for EN resistances but also for patch load resistance models which have been recently developed. By doing this it is assured that the newly developed F-M-V interaction equation is applicable to future developments. The following advanced patch load resistance models which have been mainly developed in the frame of the COMBRI research project [3] are compared besides current EN resistances:

- The proposal for girders without longitudinal stiffeners according to Gozzi [4] which follows the general procedure of current EN 1993-1-5 but which has been further developed with regard to the yield load and the reduction function.
- The proposal for girders with longitudinal stiffeners according to Davaine [5] which can be used with current EN 1993-1-5. It has been developed by adding the critical load of the directly loaded subpanel and by modifiying the reduction curve.
- Another proposal for girders with longitudinal stiffeners according to Clarin [6] which is harmonised with the improved resistance model for girders without longitudinal stiffeners according to Gozzi. It also uses the critical load of the directly loaded subpanel but here the reduction curve for unstiffened cases is also used for girders with longitudinal stiffeners.

Regardless of girders without and with longitudinal stiffeners the bending moment resistance is determined according to Section 4 and the shear resistance according to Section 5, both EN 1993-1-5 [1].

In order to evaluate the quality of the proposed interaction equations with regard to the different patch load resistance models statistical analyses are performed. In the statistical evaluation the test result R_e which can be of experimental or numerical origin is consistently compared to the calculated resistance R_t of the chosen engineering model under the same load ratio. From a constant load ratio two scalar load amplification factors can be determined. The quotient of the two scalar load amplification factors represents a key figure and on that basis a vectorial comparison is carried out for each pair of tested and calculated resistances.

5 STUDIES ON TRANSVERSE LOADING AND SHEAR FORCE (F-V)

Based on own experimental and numerical investigations in the frame of the COMBRI research project [3] a Finite Element model has been established with ANSYS® software [7] and verified with a good agreement between experimental and numerical results. With this model the complex load paths in the steel plates were followed and the interaction behaviour for varying F-V load ratio could be described. The investigations showed that the interaction between transverse loading and shear force is significant. However, current design standards such as EN 1993-1-5 [1] cover only the interaction between transverse loading and bending moment. The evaluation of proposed interaction equations from literature led to the conclusion that the proposals made on the basis of cold-formed trapezoidal beams and hot rolled sections are not applicable to slender steel plates. On the other hand the interaction equation proposed by Roberts and Shahabian [8] was approved for short loading lengths $s_s/h_w < 0.25$. For longer loading lengths, however, their interaction equation does not lead to safe results. The lack of a F-V interaction equation in EN 1993-1-5 and the results from the experimental and numerical studies indicated that for the interaction between transverse loading and shear force the formulation of an appropriate interaction equation is required. Following the principles which were set up in sections 2 and 3, interaction equation (1) has been developed.

$$\frac{F}{F_R} + \left(\frac{V - 0.5 \cdot F}{V_{b,R}}\right)^{1.6} \quad \leq \quad 1.0 \tag{1}$$

where

F_R is the transverse loading resistance of the cross section according to Section 6, EN 1993-1-5, or according to the advanced resistance models by Gozzi [4], Davaine [5] and Clarin [6];

$V_{b,R}$ is the shear resistance of the cross section according to Section 5, EN 1993-1-5.

The evaluation of the different resistance models showed that the proposed interaction equation is safe sided not only for girders without but also with longitudinal stiffeners. The statistical evaluation is given in table 1. Detailed results of the study can be found in [9].

Table 1: Statistical evaluation of the F-V interaction equation.

Model	Mean value	Standard deviation	Lower 5%-fractile
Gozzi (2007)	1.309	0.184	1.007
Davaine (2005)	1.574	0.139	1.346
Clarin (2007)	1.556	0.126	1.348

6 ENHANCEMENT OF THE F-V PROPOSAL TO BENDING MOMENT (F-M-V)

Plates under transverse loading are unavoidably subjected to bending moment so that this interaction has been already addressed in a number of research works which cannot be fully listed here. A comprehensive summary of interaction equations can be found e.g. in [10]. The statistical evaluation of the different interaction equations based on EN reference strengths is given in table 2. The Roberts proposal is the most conservative one, whereas the Bergfelt proposal is the most favourable one. However it can be shown that all proposals perform similar and that the trilinear EN approach is simple though appropriate. And although the EN interaction equation was determined on the basis of EN reference strengths, it can be shown that it could be further used for welded sections even if the advanced resistance model of Gozzi is used. However, the objective to propose a single F-M-V interaction equation led to the development of a F-M interaction equation which can be consistently merged with the F-V proposal, see equation (1).

Table 2: Statistical evaluation of F-M interaction equations in chronological order.

Model	Mean value	Standard deviation	Lower 5%-fractile
Bergfelt (1971)	1.541	0.264	1.107
Roberts (1981)	1.584	0.237	1.193
Elgaaly (1983)	1.552	0.254	1.134
Ungermann (1990)	1.567	0.239	1.174
Johansson & Lagerqvist (1994)	1.544	0.258	1.120
EN 1993-1-5 (2006)	1.548	0.255	1.128

Following the principles which were set up in sections 2 and 3, an interaction equation based on the general format according to equation (2) has been developed.

$$\frac{F}{F_R}+\left(\frac{M}{M_R}\right)^c \leq 1.0 \qquad (2)$$

Equation (2) is fitted as lower bound curve to a small FE study of Davaine and the F-M database which has been evaluated with the advanced resistance models of Gozzi and Clarin. The comparison is shown in figures 4 and 5. The difference between both figures is the reference strength which has been chosen for the bending moment resistance. Data points inside the interaction curve can be disregarded since they are close to basic loading cases so that their deviation is considered as inherent to the resistance models for the reference strengths. In figure 4 the reference strengths for the bending moment resistance M_R is based on the relevant cross-section class, i.e. M_{pl} or M_{el}. The parameter c is determined and rounded off to a single decimal place so that c = 5.0. It can be shown that for high levels of bending moment the interaction curve hardly catches the distribution of data points. For that reason, in a second step the plastic moment resistance irrespective of the cross-section class was chosen as reference strength, as it is similarly used in the M-V interaction of Section 7.1, EN 1993-1-5. The parameter c is determined and rounded off to a single decimal place so that c = 3.6. The results are shown in figure 5. It can be shown that the data is slightly more homogenouos though hardly perceptible. The statistical evaluation of both proposals which is given in tables 4 and 5 supports this. In table 3 the results of current EN rules are given and a comparison shows that in both cases an improvement exists which can be identified by comparing especially the standard deviation. However, in terms of statistical quality both proposals are almost identical.

This consistency and the data scatter which is perceived to be slightly more homogenuous leads to the adoption of the plastic bending moment resistance as reference value. Thus, the consistent definition of the F-V and F-M interaction equations as continuous function enables the merging of both criteria. The full F-M-V interaction equation becomes equation (3). In addition the resistance criteria of the basic loadings according to section 4.6, 5.5 and 6.6, EN 1993-1-5, should be met. The resulting interaction surface is illustrated in figure 6.

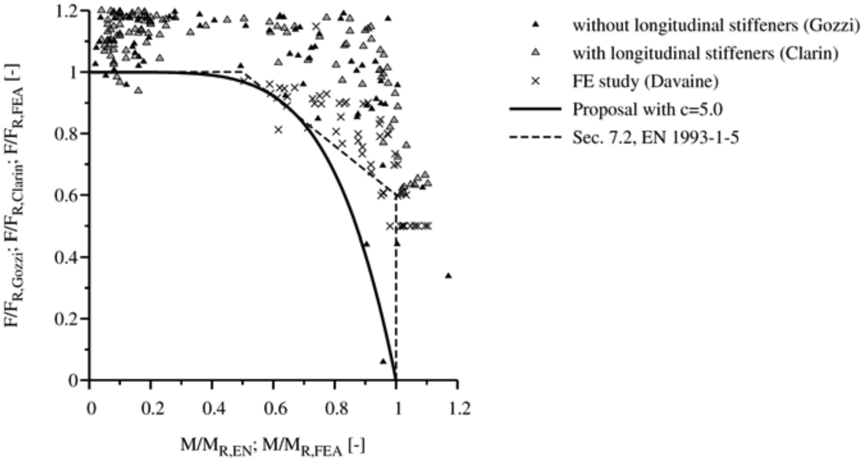


Figure 4: F-M interaction proposal, M_R based on relevant cross-section class

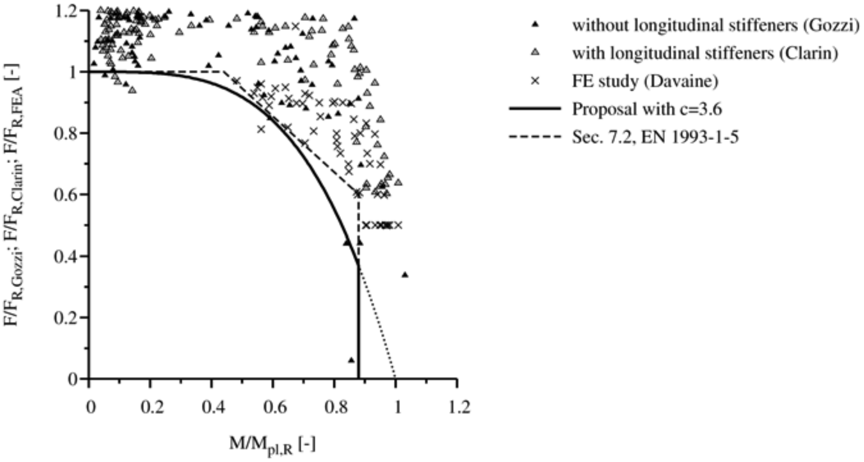


Figure 5: F-M interaction proposal, $M_R = M_{pl,R}$ irrespective of the cross-section class (here: $M_{el,R}/M_{pl,R} = 0.88$)

Table 3: Statistical evaluation of the F-M interaction equation according to EN 1993-1-5.

Girder type	Mean value	Standard deviation	Lower 5%-fractile
with longitudinal stiffeners	1.548	0.255	1.128
without longitudinal stiffeners	1.598	0.315	1.080

Table 4: Statistical evaluation of the F-M interaction equation with $M_R = M_{R,EN}$ and c = 5.0.

Model	Mean value	Standard deviation	Lower 5%-fractile
Gozzi (2007)	1.458	0.229	1.081
Davaine (2005)	1.404	0.204	1.067
Clarin (2007)	1.462	0.243	1.063

Table 5: Statistical evaluation of the F-M interaction equation with $M_R = M_{pl,R}$ and c = 3.6.

Model	Mean value	Standard deviation	Lower 5%-fractile
Gozzi (2007)	1.466	0.229	1.089
Davaine (2005)	1.414	0.204	1.078
Clarin (2007)	1.466	0.242	1.068

$$\frac{F}{F_R} + \left(\frac{M}{M_{pl,R}}\right)^{3.6} + \left(\frac{V - 0.5 \cdot F}{V_{b,R}}\right)^{1.6} \leq 1.0 \tag{3}$$

where

F_R is the transverse loading resistance of the cross section according to Section 6, EN 1993-1-5, or according to the advanced resistance models by Gozzi [4], Davaine [5] and Clarin[6];

$M_{pl,R}$ is the plastic resistance of the cross section consisting of the effective area of the flanges and the fully effective web irrespective of its section class;

$V_{b,R}$ is the shear resistance of the cross section according to Section 5, EN 1993-1-5.

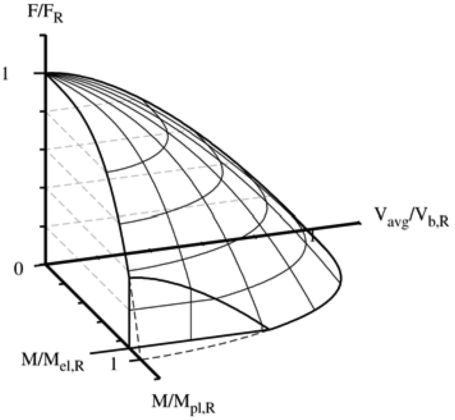


Figure 6: F-M-V interaction surface

7 CONCLUSIONS

Based on the research work of the COMBRI research project [3] and beyond [11], evident and necessary improvements regarding the interaction criteria of steel plates are reported in this paper. At the beginning thorough considerations on the formulation of interaction criteria and verification points were made in general. In detail a new interaction equation for the effective width method in case of transverse loading, bending moment and shear force has been proposed which is summed up below.

First a comparison of the experimental and numerical F-V results with known tests from literature showed that the interaction between transverse loading and shear force is not negligible. A comparison with proposals from literature showed that only few approaches exist which do not appropriately describe the interaction behaviour e.g. with regard to the influence of the long loading lengths. Especially for longer loading lengths the formulation of a new interaction equation was required, see equation (1). By choosing the verification point at the centerline of the transverse loading the part of the shear force which is induced by the transverse loading and which is already included in the resistance model can be accounted for. As a result not only the smallest data scatter is found but also a conclusive subdivision of the interaction case into the basic loadings "transverse loading" and "shear force" is possible which makes an interaction verification for a transverse loading without additional shear force obsolete.

Plates under transverse loading are unavoidably subjected to bending moment so that this interaction has already been addressed in a number of research works which have been thoroughly evaluated in this work. The performance of all proposals is similar and it could be shown that the trilinear EN approach is simple though appropriate. However, the objective to propose a single F-M-V interaction equation led to the development of a F-M interaction equation which can be consistently merged with the F-V proposal, see equation (3). The verification point is naturally chosen at the centerline of the transverse loading which is the location where also the maximum bending moment occurs.

The new formulation is based on the experimental and numerical data set from own work and from literature and a statistical evaluation proves the applicability of the equation not only to current EN resistance models but also to the improved resistance models developed by Gozzi, Davaine and Clarin, for unstiffened and for longitudinally stiffened girders.

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