Design of High Strength Steel Longitudinal Stiffened Plate Girders Loaded with combined Bending, Shear and Compression

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1. Project description and goals

The numerical analysis of S690 high-strength steel plate girders with welded sections, stiffened longitudinally and transversely, loaded under combined bending, shear, and compression is the focus of this study (Fig.1). The combined N-M-V interaction should be considered in the design of these steel I-girders to assure their safety. This interaction can be evaluated using the formulas in the current version of EN1993-1-5 [1], but it is well recognized that this formula does not accurately reflect the true interaction of the forces (Fig. 2).

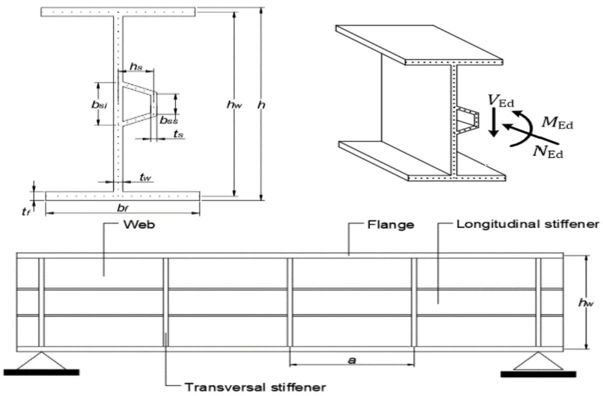


Fig. 1: Design of S690 slender plate I-girders under combined bending, shear and compression

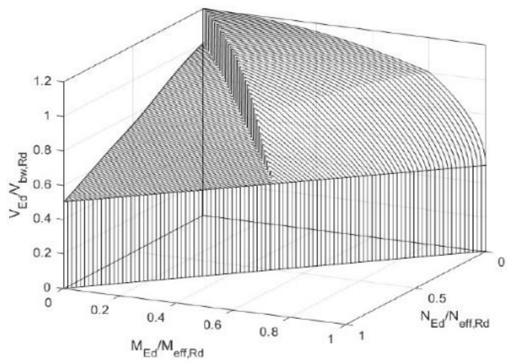


Fig. 2: N-M-V interaction diagram given by prEN1993-1-5 [2]

The N-M-V interaction design formulation using the Effective Width Method (EWM) was proposed to be modified by Biscaya [3]. The primary objective of this study is to evaluate this formulation for HSS S690 longitudinally stiffened plate girders, with the goal of determining the ideal location for the longitudinal closed stiffener in order to reduce the amount of material required. Furthermore, the Reduced Stress Method (RSM) as defined in EN1993-1-5 is well known for not being a very cost-effective design process. As a result, the possibility of incorporating stress shedding into the RSM formulation is proposed and tested to make this method more structurally efficient and produce more sustainable designs.

2. Numerical model and results

Five plate girder designs were chosen to evaluate structural behaviour and determine the optimal position of the longitudinal stiffener. The plate girder geometries contain the following parameters: $h_w/t_w = 80\,\text{mm}$; $h_w = 1000\,\text{mm}$; $b_{si} = 100\,\text{mm}$; $b_{ss} = 50\,\text{mm}$; $\gamma = 50$; $\alpha = 1$; $A_f/A_w = [0\,;1.0]$, and one closed longitudinal stiffener at $0.50\,h_w$, $0.60\,h_w$, $0.67\,h_w$, $0.75\,h_w$ or $0.80\,h_w$.

Abaqus-Python [4] interpreter code and Matlab subroutines were used to create several numerical models. Figure 3 shows the three-panel FEM model adopted, which is loaded with 49 different N-M-V load combinations at the web vertical edges. The Modified Riks Method [5] is used in the analysis, which includes equivalent geometric imperfections based on the combination of buckling mode shapes, and material non-linearity (GMNIA) using HSS S690.

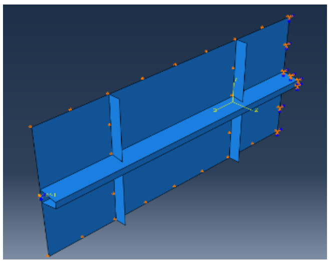


Fig. 3: Abaqus numerical model

Figure 4 shows the N-M and M-V interactions for diferent plate girder configurations with and without flanges (which corresponds to place the stiffener at h_w). For a plate girder with strong flanges ($A_f/A_w = 1$) with N,M,V individual loadings, it can be concluded that using the middle stiffener is the best compromise. In the absence / weak flanges ($A_f/A_w = 0$) it is important to move the stiffener up because there is a significant increase in bending resistance.

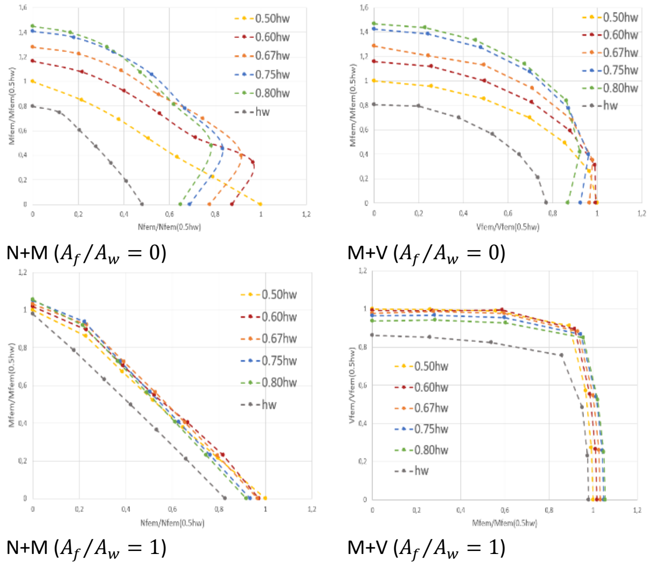
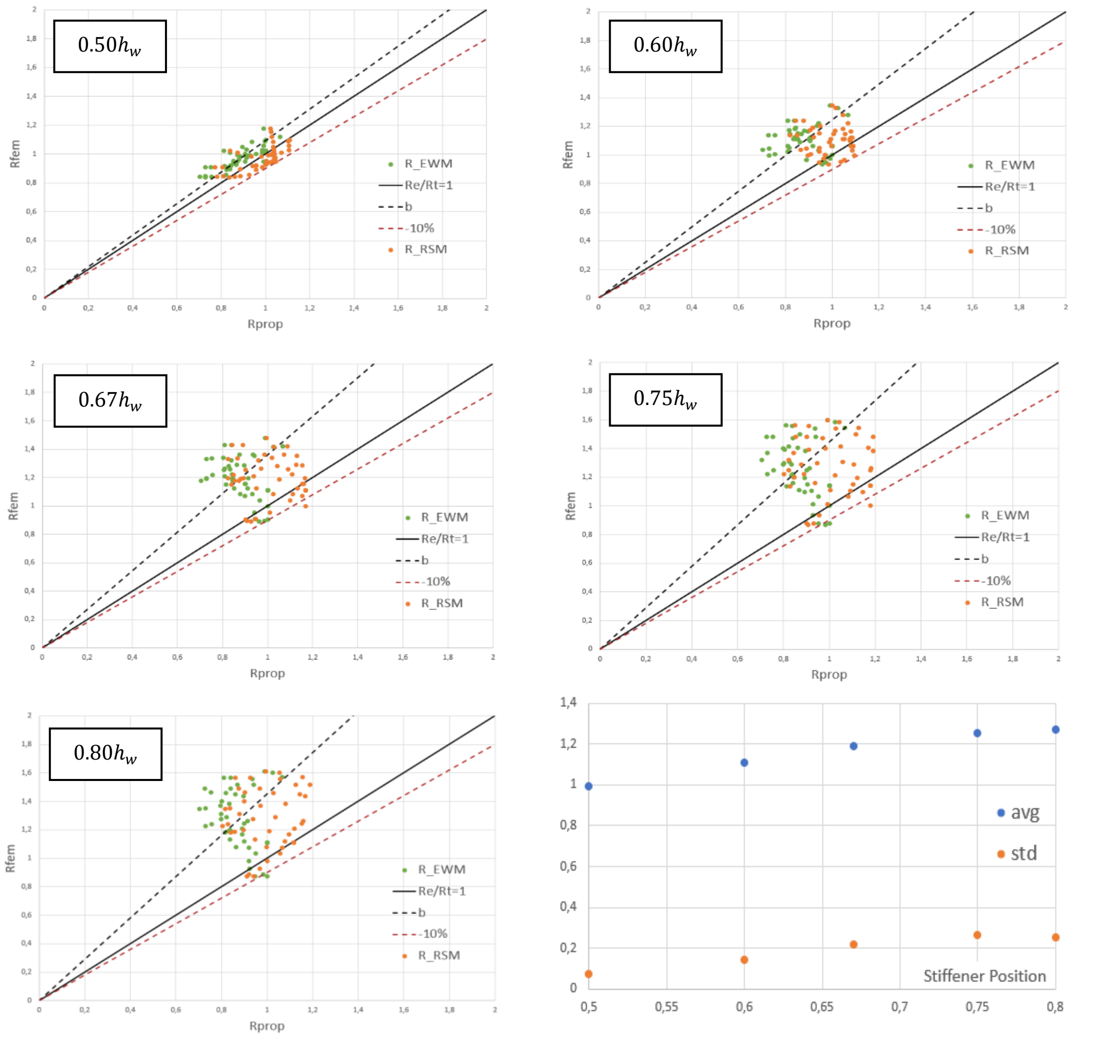


Fig. 4: N-M and M-V interaction for stiffened plate girders with different stiffener positions

Moving the stiffener towards the compressed flange enhances the web resistance as it prevents local buckling of the top web sub-panel. For plate girders with strong flanges, the stiffener position becomes significantly less important. Finaly, for N-M-V loadings, the stiffener must be placed based on the governing load.

Figure 5 shows the results of the N-M-V interaction obtained using the EWM and the RSM for two A_f/A_w ratios (= 0; with no flanges, = 1; with strong flanges) and compares them to the FEM results. The dispersion of the results is substantially higher for stiffened web plates with no flanges, and the new EWM interation results are generally conservative, albeit the RSM can produce unsafe results for certain geometries. When the flanges are added, the plate girder behaviour becomes much more stable, and the resistances derived by numerical analysis and the new EWM interation have a significantly smaller dispersion. For this case the RSM results are in general more conservative. Because the individual code resistances to M and V became more conservative as the stiffener moves up, the results tend to become more scattered in all cases, as it can be concluded by the increase of the average (avg) and standard deviation (std) statistical results (Fig.5).



$R_{FEM}/R_{EWM,RSM}$ ($A_f/A_w = 0$)

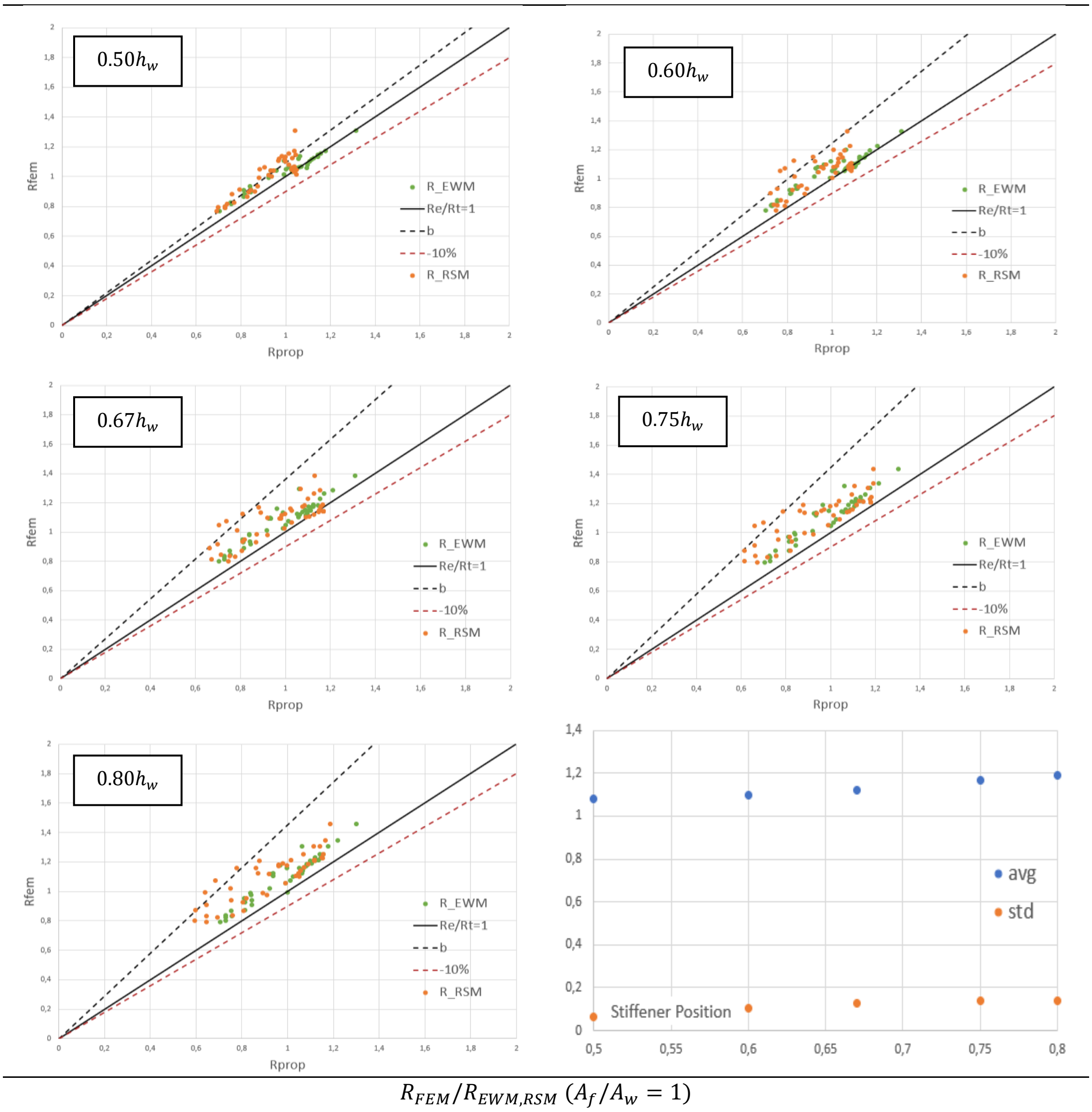


Fig. 5: $R_{FEM}/R_{EWM,RSM}$ for plate girders with five longitudinal stiffener positions and $A_f/A_w = 0$ and $A_f/A_w = 1$

Figure 6's new N-M-V resistance surface was created using the new proposal [3], which removed the non-existent discontinuity of Figure 2. The results of the numerical FE models are also shown, demonstrating in general the excellent agreement between the two sets of results, especially for plate girders with strong flanges.

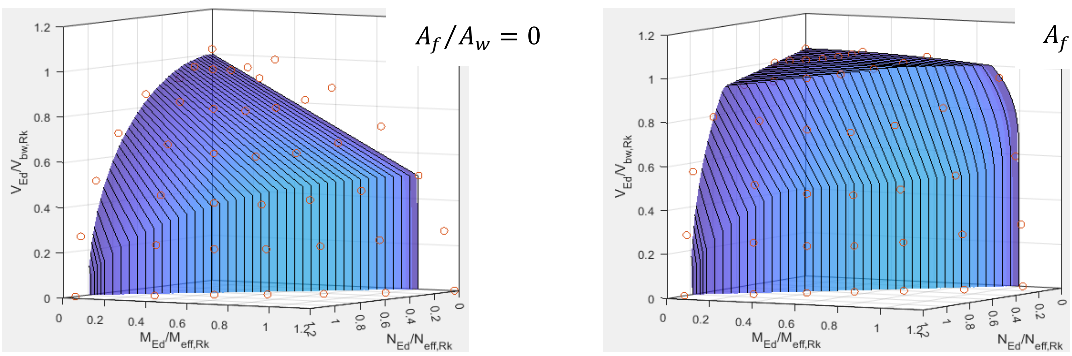


Fig. 6: $R_{FEM}/R_{EWM,PROP}$ for plate girders with a longitudinal stiffener at 0.50 h_w and $A_f/A_w = 0$ or 1.0

3. Reduced stress method with stress shedding formulation

In view of the previous results, the RSM in EN 1993-1-5 can be enhanced by incorporating a controlled stress shedding from the web to the flanges, making it less conservative. The approach from the old BS 5400 – Part 3 [6] was revisited. The applied internal forces N-M-V can be expressed as a function of k, which reflects the fraction of direct stress that remains in the web. The approach is described in detail in Biscaya and Baguinho works [3,7]. When this stress shedding is considered, the RSM+S yields significantly better results than the RSM as in EN 1993-1-5 [1], as shown in Figure 7 for the case of the N loading. The coefficient k tends to decrease when the longitudinal stiffener is moved up (Figure 8), indicating that there is a better possibility of redistribution even though there are still a lot of normal stresses left in the web (between 0.65 and 0.85).

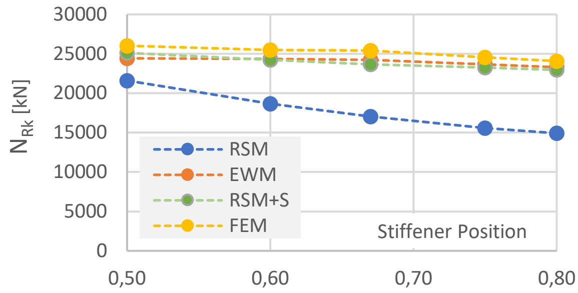


Fig. 7: Comparison of the pure compression resistance between the three methods and the FEM results

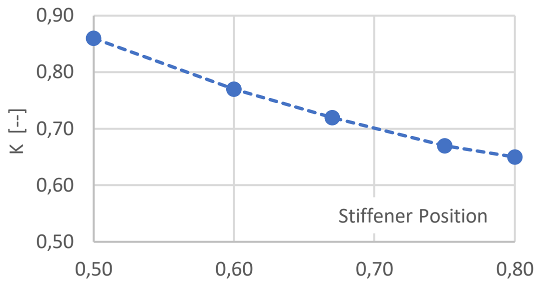


Fig. 8: Values of coefficient k for the different stiffener positions

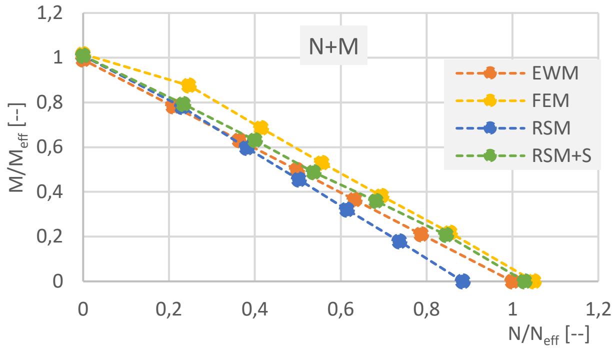


Fig. 9: Interaction N-M for the three methods and the FEM results

The comparison of the N-M interaction for the various load cases is shown in Figure 9. The RSM+S displays the N-M interaction results that are the most similar to those obtained using FEM models. When the stiffener is at mid-height, both the EWM and the RSM+S generate an almost linear interaction; however, the EWM's N and M resistances are a little more conservative. In conclusion the RSM+S is a very consistent and elegant method for evaluating the ULS resistance of longitudinal stiffened plate girders.

4. Conclusions and potential for application of the results

The following conclusions can be taken from the MSc research work:

- The novel N-M-V interaction formulas [3] are well calibrated for high strength steel S690 plate girders with variable longitudinal stiffener placements.
- The longitudinal stiffener should be placed in the middle of the panel for N and V loadings; for high M loadings, the stiffener should be moved up to the compressive region of the web; for N-M-V loadings, the ideal position of the longitudinal stiffener is determined by the controlling internal force.
- For plate girders with strong flanges, the RSM provides in general lower N-M resistances than the EWM because it ignores the flange contribution.
- Finally, the RSM+S with stress shedding as presented produces consistent and remarkably accurate results, which are the most similar to the numerical models' ultimate resistances.

The following are some of the potential applications of the results in the field of plated girder structure design:

- By knowing the ideal position of the longitudinal stiffener when subjected to various loadings, it can achieve a more competitive and sustainable design while using less material.
- The RSM's enhancements, which include the possibility of considering the stress shedding from the web to the flanges, allow for the design of very competitive plated girder structures by applying a design method that has proven to be very versatile and capable of dealing with steel plated structures with complex geometries and multiaxial loadings.

5. References

[1] EN 1993-1-5 – *Eurocode 3 – Design of steel structures – Part 1-5: Plated structural elements*, CEN, 2005.

[2] prEN 1993-1-5 – *Eurocode 3 – Design of steel structures – Part 1-5: Plated structural elements*, CEN, 2021.

[3] A. Biscaya – *Buckling resistance of steel plated girders considering M-V interaction with high compression forces*, PhD thesis, IST, University of Lisbon, 2021.

[4] SIMULIA, *Abaqus Scripting User´s Manual. Dassault Systems*, 2011.

[5] B. Falzon; M. Aliabadi – *Buckling and Post-buckling Structures, Experimental, Analytical and Numerical Studies*, Computational and Experimental Methods in Structures – vol. 1, Imperial College Press, London, 2008.

[6] BS 5400 – Part 3 – *Steel, concrete and composite bridges*, British Standard institute, London, 1983.

[7] F. Baguinho – *Design of High Strength Steel Longitudinal Stiffened Plate Girders Loaded with combined Bending, Shear and Compression,* MSc dissertation, IST, University of Lisbon, 2021.