# DESIGN, FABRICATION AND ECONOMY OF WELDED STRUCTURES

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# 3.1 Optimization of Steel Beams and Columns for Variable Rib Configuration

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Abstract

*Optimal configuration of stiffening ribs in the steel welded I – beams and columns is studied. A wide class of designs with traditional orthogonal configuration implementing transverse and/or longitudinal ribs is considered and compared with a new configuration with diagonal ribs. The critical load and the total manufacturing cost, composed of costs of steel, cutting and welding are computed for all designs. The configuration with diagonal ribs proved to be more efficient than the traditional ones.*

Keywords: *stability analysis, local buckling, steel welded girders, optimization.*

## 1 Introduction

Welded steel girders have found wide application in modern steel structures. Steel beams produced from very thin steel sheets are advantageous from economical reasons. However, these structures demonstrate great tendency towards local instability and are sensitive to initial geometric imperfections. Moreover, when local buckling load coincides with, or is closed to global one, we face an interactive buckling. It can result in high sensitivity to imperfections and often to unstable post-buckling behaviour.

The disadvantageous influence of local instability can be reduced by application of transverse stiffeners. The optimal detailing of transverse stiffeners is not a trivial task. In optimal designing of girders in 4-th class of cross section, the aim is to find configuration of ribs, which minimizes the influence of local instability and simultaneously it must provide a design which is less expensive than a girder in 3-rd class of cross section.

Actual design codes provide practical design recommendations with respect to local instability of web only when the transverse stiffeners are orthogonal to girder's web and flange plates. In this case the problem of local instability can be limited to the square or rectangular plate representing the part of the web between ribs. Influence of the local instability is usually accounted for by the coefficient $\chi$ as a function of plate slenderness $\bar{\lambda}$ (ENV 1993-1-1 1992). This approach cannot be applied to diagonal ribs. Moreover, it does not take into consideration the interactive buckling, when local and global instability appears at the same load level.

The influence of rib configuration on the load capacity of the beam was discussed in Chybiński et al. (2007), Rzeszut et al. (2004) and Shahabian & Haji-Kazemi (2005). The dependency of stiffness of the head plates on the critical bending moment in the lateral buckling was studied experimentally in Lindner & Gietzelt (1984) and numerically in Kurzawa et al. (2005). In Szymczak et al. (2001) a supper element suitable for numerical modelling of the thin-walled members with different rib configuration was proposed. The influence of initial imperfections on buckling and post-buckling behaviour was studied in Rzeszut et al. (2004) using non-linear stability analysis with Riks method.

In this paper stability analysis of steel girders with transverse and longitudinal stiffeners for a wide range of beam lengths and rib dimensions and configurations is presented. One can expect simultaneous local and global buckling. Therefore, FEM is used employing shell elements implemented in general proposed program ABAQUS (2001). Hence, the global and local buckling modes can be captured for all rib configurations.

## 2 Formulation of the problem

The linear stability analysis is performed using FEM with rectangular four-node shell elements S4R with reduced integration and 6 DOF in each node. Vlasov beam theory in continuous formulation was used for comparison. The linear eigenvalue problem had the classical matrix form:

$$(\mathbf{K}^{O} + \lambda \mathbf{K}^{G*})\mathbf{U} = \mathbf{0}, \tag{1}$$

where: $\mathbf{U}$, $\lambda$ and $\mathbf{K}^{G*}$ denote eigenvector, load multiplier and geometric matrix, respectively. The efficiency of various configurations and dimensions of ribs is studied for beams and columns. However, the major part of the study is devoted to beams, since the state of stress in webs of beams and local buckling phenomena are more complex due to high shear effects.

In numerical analyses concerning beams the I-section 1250x10x260x24mm was assumed with varying span lengths $L$ = 5.0; 7.5 and 10.0m. The calculations were carried out for different rib dimensions and configuration including diagonal ones (Fig. 2). Theoretical "fork" supports with unconstrained warping were modelled (Fig. 1).

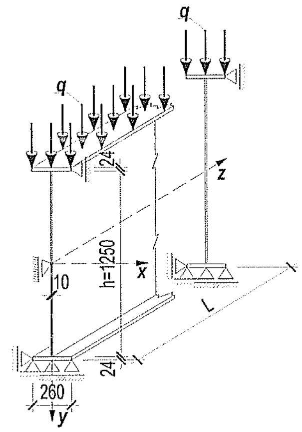


Figure 1. Dimensions of the beam, supporting constraints and the loading q.

The influence of the number of ribs and their thickness on the critical buckling load was carried out on a set of five beams shown in Fig. 2. Thickness of ribs was 4 and 12mm. FEM shell elements were employed. For comparison Vlasov buckling load was computed, too.

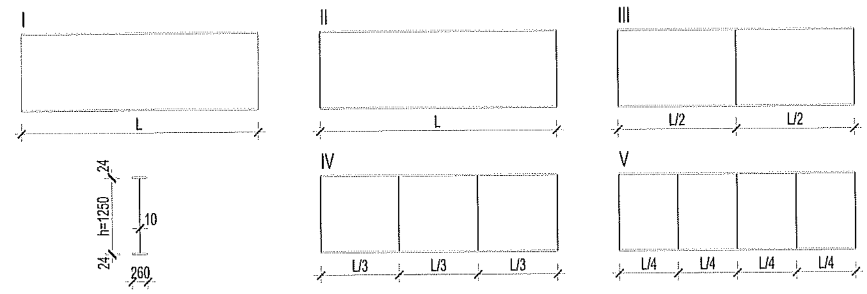


Figure 2. The set of 5 beams. Thickness of ribs 4 and 12mm. (I) Beam without ribs. (II) Ribs (head-plates) at supports. (III)-(V) Ribs at supports and in span.

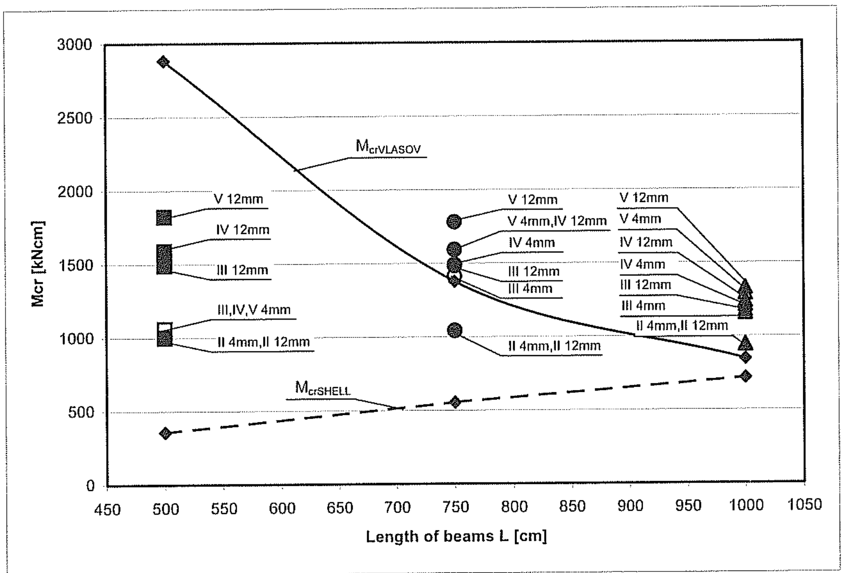


Figure 3. Critical bending moments $M_{cr}$. Solid line: Vlasov theory. Dashed line and points: shell elements. Greek numbers II –V refer to beams shown in Fig. 2. Open circles, squares and triangles refer to webs 4 mm.

The results of the stability analysis are shown in Fig 3. Note that the vertical axis in Fig. 3 represents the bending moment of simply supported beam $M= 0.125 \cdot qsL^2$, where $s$=26cm is the width of flange. Convergence of solid line (Vlasov theory) to the dashed line (shell elements) for increasing length of beams confirms the well known assumption of Vlasov theory, that the length of beam is sufficiently long, namely $L \geq 10H$. In our case $H$=1298+48=1298mm and $L \leq 13.0$m, therefore the Vlasov theory cannot be applied. Analyzing the results represented by points one observes radical increase of critical moment with increase of number of ribs. This result was expected, since in case of short beams the essential role is played by the local buckling. Rather unexpected were small differences in $M_{cr}$ due to variable thickness of head-plates and ribs (4mm and 12mm).

The main part of the study concerns the efficiency of ribs with variable configuration. More than 20 configurations were analyzed. Eight of them will be discussed in the paper. Fig. 4 illustrates four beams with diagonal ribs, which will be compared with four traditional orthogonal rib configurations. The length of all beams is 10.0m. The cross-sectional dimensions, supporting constraints and the loading q is shown in Fig. 2. The thickness of all ribs is 12mm. The longitudinal stiffeners in models 7 and 8 have the same thickness and width as transverse ribs in all models. The longitudinal stiffeners are located in the zone of compressive stress, namely at $2h/3$ from the bottom flange. Therefore, in model 7 they are concentrated in middle part of the span, where maximum bending moment appears.

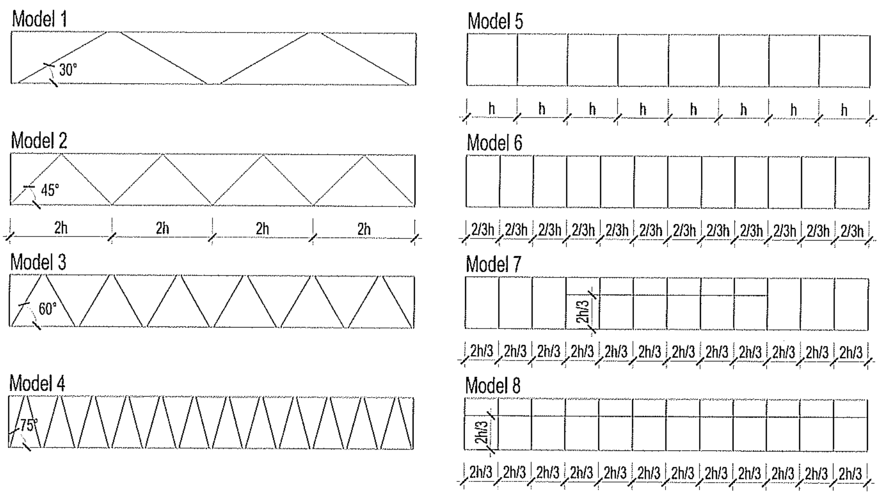


Figure 4. Various configurations of ribs. Models 1-4: diagonal ribs with inclination angles $\alpha$= 30°, 45°, 60°, 75°. Models 5-8 orthogonal ribs.

## 3 Influence of ribs' configuration on critical buckling moment and on manufacturing cost

The models considered in the analysis and the results are presented in Table 1. The first three columns specify the model, namely its number referring to Fig. 4, the angle of inclination of ribs $\alpha$ and the total number of stiffening ribs $n_s$ as the sum of numbers of vertical ribs $n_v$, horizontal $n_h$ and diagonal $n_d$ .

The buckling load multipliers $\lambda_{cr}$ and hence the buckling bending moments $M_{cr}$ were computed for all beams using FEM with shell elements. The critical buckling moment is presented in 4-th column of the table 1. The 5-th column presents the total length of fillet welds connecting flanges to the web and ribs to the I-section. The next column gives the total mass of the beam. The round bracketed numbers in columns 5 and 6 specify the total length of welds connecting ribs and the total mass of ribs, respectively. The last column gives the total manufacturing cost of beams.

The total manufacturing cost was assessed using the specific unit costs of material (steel), cutting and welding. These unit costs were obtained from a medium-sized company in Poland, specialized in production of steel structures. The prizes were actual in October 2007. Cutting cost of steel sheets was estimated for gas cutting.

The cost of fillet welding refers to metal active gas welding (MAG welding) in process (process number is 135) EN ISO 4063 (2000), which provides continuous welds, both fillet and butt welds. It was assumed that for the connection of flanges to the web the double-bevel butt welds 12mm, are used, whereas stiffening ribs are connected to I-section using fillet welds 5mm. Specific unit cost of the butt weld 12 mm was 1.2€/m. For the fillet weld 5mm it was 0.51€/m. Cost of cutting was assessed basing on specific unit costs of cutting steel sheets: thickness 24mm – 0.84€/kg, thickness 12mm and 10mm – 0.11€/kg. Unit cost of material also depended on the thickness of steel sheets, namely: thickness 24mm – 0.82€/kg, thickness 12mm and 10mm – 0.64€/kg.

Table 1. Efficiency of various configurations of stiffening ribs

| *model* | $\alpha$ [°] | $n_s = [n_v, n_h, n_d]$ | $M_{cr}$ [*kNcm*] | $l_w$ ($l_{fw}$) [*cm*] | $m_t$ ($m_r$) [*kg*] | *Total cost* [€] |
|---|---|---|---|---|---|---|
| Model 1 | 30 | 12 = [4,0,8] | 195471 | 9600 (7600) | 2255 (294) | 1949 |
| Model 2 | 45 | 20 = [4,0,16] | 282107 | 11664 (9664) | 2353 (392) | 2033 |
| Model 3 | 60 | 28 = [4,0,24] | 312508 | 13328 (11328) | 2427 (467) | 2097 |
| Model 4 | 75 | 52 = [4,0,48] | 323370 | 20023 (18023) | 2751 (790) | 2371 |
| Model 5 | 90 | 18 = [18,0,0] | 159276 | 9400 (7400) | 2225 (265) | 1927 |
| Model 6 | 90 | 26 = [26,0,0] | 171351 | 11800 (9800) | 2343 (383) | 2026 |
| Model 7 | 0, 90 | 38 = [26,12,0] | 207021 | 14370 (12370) | 2459 (499) | 2126 |
| Model 8 | 0, 90 | 50 = [26,24,0] | 218119 | 16940 (14940) | 2575 (615) | 2225 |

Table 1 demonstrates that the configuration of diagonal ribs is surprisingly efficient in comparison with traditional orthogonal ribs. Let us compare the values of buckling moment $M_{cr}$ of beams with diagonal ribs with beams with orthogonal configuration. Compare diagonal model 1 (cost 1949EU, $M_{cr}$ = 1955kNm) with model 5 (cost 1927EU, $M_{cr}$ = 1593kNm). We observe 23% increase of $M_{cr}$ by approximately same price. Compare now diagonal model 2 (cost 2033EU, $M_{cr}$ = 2821kNm) with model 6 (cost 2026EU, $M_{cr}$ = 1714kNm). We observe 65% increase of $M_{cr}$ by approximately same price. Finally compare diagonal model 3 (cost 2097EU, $M_{cr}$ = 3125kNm) with model 7 (cost 2126EU, $M_{cr}$ = 2070kNm). The increase of $M_{cr}$ is 51%. The first author has also developed a study of the post buckling response of the beams with diagonal ribs. The results confirmed the advantage of this configuration. The problem will be further studied.
The results of the analysis of columns will be presented at the conference.

## 4 Concluding remarks

A study of the efficiency of various configurations and thickness of stiffening ribs in welded steel beams of I-section is presented in the paper. The simply supported beams subjected to uniformly distributed load were considered. The dimensions of beams (4-th slenderness class) showed that the local buckling played an essentia role. The bearing capacity was computed from linear stability analysis using FEM with shell elements.

The configuration of diagonal ribs was studied as an alternative to traditional orthogonal transverse and/or longitudinal stiffening ribs. The bifurcation critical bending moments $M_{cr}$ and the total manufacturing costs were computed for a set of different configurations of ribs. In the assessment of the total cost, special attention was paid to implement actual specific unit costs of steel, cutting and welding.

The analyses demonstrated that the configuration with diagonal ribs provides surprisingly efficient solutions. The beams with diagonal ribs demonstrate 20% - 65% increase of $M_{cr}$ compared to the beams of the same cost but with orthogonal ribs. This was already shown in Chybiński et al. (2007). The originality of this paper is that it demonstrates that the increase of $M_{cr}$ is gained without increase of the total cost, which was assessed basing on actual unit prices.

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