optimization of high strength steel structures

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contents

• high strength steel (HSS) in structural design
• welded beams
• tubular trusses

research carried out as part of RFCS project "RUOSTE" (Rules on High Strength Steel)
HSS in design

- **HSS**: yield strength greater than 460 MPa

- **Eurocode**: additional rules for steel grades up to S700 (EN 1993-1-12)

- **Motivation**: utilise increased strength to reduce the weight (cost) of structures
factors against HSS

• greater unit fabrication costs

• less available profiles (class 1 or 2)

• larger weld size for full strength welds (S355: 1.11t, S500: 1.61t, S700, 1.65t)

• tubular joints: strength must be reduced by 20%

overall economical benefits not evident
welded beams
welded beams

- minimize weight and cost (separately)
- steel grades: S355, S500, S700, including hybrids
- three different spans, three different loads

![Diagram of welded beam](image)
Manufacturing process and material flow

The layout of the virtual workshop and erection site shown in Fig. 8 is presented to clarify the process of delivering a steel structure project. The workshop is able to handle assembly with maximum dimensions of $L \times W \times H = 1,500 \times 2,000 \times 800$ mm.

Fig. 8. Workshop’s and site’s material flow and cost centres.

### Cost components

When calculating a cost, it is essential to use components that correspond to the purpose of the calculation. If only the manufacturing costs of two optional joints that require about the same amount of material and kind of work (say welding) are compared, only the labour cost component is needed. But when comparing totally different types of joints, say hinged versus rigid, which may also affect the dimensions of the main profile and require different fabrication processes and amount of erection work, then all available cost components must be used to get reliable results.

The cost comparisons found in literature commonly include material and labour cost components, and in some cases also equipment cost, transporting cost and erecting cost (Pavlovčič et al. 2000). The real estate cost component of cost centres was not found in any of the references.

If erection cost is based only on the:

- Material
- Blasting
- Sawing
- Welding
- Painting
- Transport
- Erection

Feature-based costing method (Haapio 2012)
General form of costs in single cost centre:

\[
C_k = \frac{(T_{Nk} + T_{Pk}) (c_{Lk} + c_{Eqk} + c_{Mk} + c_{Rek} + c_{Sek})}{u_k} + T_{Pk} (c_{Ck} + c_{Enk}) + C_{Ck}
\]
cost evaluation

General form of costs in single cost centre:

\[ C_k = \frac{(T_{Nk} + T_{Pk}) (c_{Lk} + c_{Eqk} + c_{Mk} + c_{Rek} + c_{Sek})}{u_k} + T_{Pk} (c_{Ck} + c_{Enk}) + C_{Ck} \]
cost evaluation

General form of costs in single cost centre:

\[ C_k = (T_{N_k} + T_{P_k}) \left( \frac{c_{L_k} + c_{E_{q_k}} + c_{M_k} + c_{R_{e_k}} + c_{S_{e_k}}}{u_k} \right) + T_{P_k} (c_{C_k} + c_{E_{n_k}}) + C_{C_k} \]
cost evaluation

General form of costs in single cost centre:

\[
C_k = \frac{(T_{Nk} + T_{Pk})}{u_k} \left( c_{Lk} + c_{Eqk} + c_{Mk} + c_{Rek} + c_{Sek} \right) + T_{Pk} (c_{Ck} + c_{Enk}) + C_{Ck}
\]
cost evaluation

General form of costs in single cost centre:

\[ C_k = \frac{(T_{Nk} + T_{Pk}) (c_{Lk} + c_{Eqk} + c_{Mk} + c_{Rek} + c_{Sek})}{u_k} + T_{Pk} (c_{Ck} + c_{Enk}) + C_{Ck} \]

- NON-PRODUCTIVE TIME
- PRODUCTIVE TIME
- UNIT COSTS FOR LABOUR, EQUIPMENT, MATERIALS, AND REAL ESTATE [€/MIN]
- UNIT COSTS FOR CONSUMABLES AND ENERGY [€/MIN]
COST OF TIME-INDEPENDENT CONSUMABLES [€]

UNIT COSTS FOR CONSUMABLES AND ENERGY [€/MIN]

UNIT COSTS FOR MATERIALS, LABOUR, EQUIPMENT, AND REAL ESTATE [€/MIN]

NON-PRODUCTIVE TIME

PRODUCTIVE TIME

where $C$ is the set of cost centres and $C_k$ is the cost at cost centre $k$ [€]. The cost centres considered in this document, and their symbols are shown in Table 1.1.

The general form of the cost generated in cost centre $k$ is

$$C_k = \left( T_{N_k} + T_{P_k} \right) \left( c_{Lk} + c_{Eqk} + c_{Mk} + c_{Rek} + c_{Sek} \right) + T_{P_k} \left( c_{Ck} + c_{Enk} \right) + C_{Ck}$$

The symbols appearing in Eq. (1.2) are explained in Table 1.2.

The general form can be used in any of the cost centres. In order to apply Eqs. (1.1) and (1.2) for given steel structure type (e.g. welded beam, tubular truss), the main task is to identify the relevant cost centres and to devise the expressions of the related cost factors as functions of the parameters of the structure. This requires a thorough knowledge and preferably measured data of the processes used in the chosen workshop.

1.1.1 Real estate costs

Real estate investment costs consist of the price of the land of the building. On the other hand, maintenance cost depends on the space occupied by the building. The unit cost of the real estate, $c_{Re_0}$ [€/m²], is obtained from the following expression

$$c_{Re_0} = C_{Re}C_{Ck} + c_{lk}P_{rk}$$

General form of costs in single cost centre:
General form of costs in single cost centre:

\[
C_k = \frac{(T_{N_k} + T_{P_k})}{u_k} (c_{L_k} + c_{E_{eq_k}} + c_{M_{k}} + c_{R_{eq_k}} + c_{S_{eq_k}}) + T_{P_k} (c_{C_k} + c_{E_{nk}}) + C_{C_k}
\]
## Cost Factors

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>S355</th>
<th>S500</th>
<th>S700</th>
</tr>
</thead>
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<tr>
<td>Material</td>
<td>1.0</td>
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<td>1.3</td>
</tr>
<tr>
<td>Sawing</td>
<td>1.0</td>
<td>1.15</td>
<td>1.3</td>
</tr>
<tr>
<td>Welding</td>
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<td>1.25</td>
<td>1.5</td>
</tr>
<tr>
<td>Cutting</td>
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<td>1.0</td>
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</tr>
</tbody>
</table>

Material cost of plates (S355): 0.7 €/kg
I-beam: weight minimization

Both the weight minimization and minimum cost problems were solved by the particle swarm algorithm (PSO) (Kennedy and Eberhart, 1995; Poli et al., 2007). In the literature, many possibilities regarding the details of the algorithm are available. In this study, an implementation of the PSO method was produced, with chosen constraint handling mechanism, velocity update rules with inertia term, craziness effect and elite particle. Furthermore, whenever the best feasible solution was updated, a neighborhood search was performed, i.e. better solutions were searched in a neighborhood of the solution. Detailed description of the algorithm is beyond the scope of this paper.

Three spans of 6m, 8m, and 10m were considered with three different loads, $q = 20$, $q = 60$, and $q = 100$. For the three available steel grades, S355, S500, and S700, altogether 14 combinations could be formed for each span and load. The only restriction was that the grade of the web cannot be greater than the grade of either of the flanges.

In each case, the design values of the bending moment and shear forces are:

\[
M_{Ed} = \frac{1}{8}qL^2 \\
V_{Ed} = \frac{1}{12}qL
\]

### Weight Minimization

As a first step, it is interesting to compare the homogenous S500 and S700 cross-sections with the homogenous S355 profile, which works as the reference case. In Table 2, the ratios of the minimum weights of S500 to S355 and S700 to S355 are shown for different loads and spans. It can be seen that for the lowest load, $q = 20$, only marginally savings can be achieved by HSS. This is partly explained by the allowable plate dimensions, that are not more favourable to HSS. On the other hand, the HSS solutions are mostly restricted by the displacement constraint where the higher strength does not play any role. For the S355 solution, the moment resistance constraint is dominant, even though the utilization ratio of the displacement constraint is also more than 90%.

For higher loads, the weight savings provided by the higher strength gets more significant. For the intermediate load $q = 60$, S500 gives a savings of about 15%, whereas S700 reduces the weight by about 25%. For the largest load, and largest span, the weight reductions are 23% for S500 and 35% for S700.

### Table 2: Results of weight minimization.

The numbers are the ratios $W^{\ast}_{500}/W^{\ast}_{355}$, and $W^{\ast}_{700}/W^{\ast}_{355}$, where $W^{\ast}_y$ is the minimum weight of the homogenous cross-section with yield strength $f_y$.

<table>
<thead>
<tr>
<th>S500</th>
<th>Span (m)</th>
<th>S700</th>
<th>Span (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Load</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0.98</td>
<td>0.97</td>
<td>0.90</td>
</tr>
<tr>
<td>60</td>
<td>0.85</td>
<td>0.84</td>
<td>0.84</td>
</tr>
<tr>
<td>100</td>
<td>0.84</td>
<td>0.84</td>
<td>0.77</td>
</tr>
</tbody>
</table>
Both the weight minimization and minimum cost problems were solved by the particle swarm algorithm (PSO) (Kennedy and Eberhart, 1995; Poli et al., 2007). In the literature, many possibilities regarding the details of the algorithm are available. In this study, an implementation of the PSO method was produced, with chosen constraint handling mechanism, velocity update rules with inertia term, craziness effect and elite particle. Furthermore, whenever the best feasible solution was updated, a neighborhood search was performed, i.e. better solutions were searched in a neighborhood of the solution. Detailed description of the algorithm is beyond the scope of this paper.

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In each case, the design values of the bending moment and shear force are:

\[ M_{Ed} = \frac{1}{8} q L^2 \]
\[ V_{Ed} = \frac{1}{2} q L \]

Weight Minimization

As a first step, it is interesting to compare the homogenous S500 and S700 cross-sections with the homogenous S355 profile, which works as the reference case. In Table 2, the ratios of the minimum weights of S500 to S355 and S700 to S355 are shown for different loads and spans. It can be seen that for the lowest load, $q=20$, only marginal weights saving could be achieved by HSS. This is partly explained by the allowable plate dimensions, that are not more favourable to HSS. On the other hand, the HSS solutions are mostly restricted by the displacement constraint where the higher strength does not play any role. For the S355 solution, the moment resistance constraint is dominant, even though the utilization ratio of the displacement constraint is also more than 90%.

For higher loads, the weight savings provided by the higher strength gets more significant. For the intermediate load $q=60$, S500 gives a saving of about 15%, whereas S700 reduces the weight by about 25%. For the largest load, and largest span, the weight reductions are 23% for S500 and 35% for S700.

<table>
<thead>
<tr>
<th>S500</th>
<th>Span (m)</th>
<th>S700</th>
<th>Span (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>6 8 10</td>
<td>Load</td>
<td>6 8 10</td>
</tr>
<tr>
<td>20</td>
<td>0.98 0.97 0.90</td>
<td>20</td>
<td>0.98 0.97 0.90</td>
</tr>
<tr>
<td>60</td>
<td>0.85 0.84 0.84</td>
<td>60</td>
<td>0.76 0.74 0.73</td>
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<td>100</td>
<td>0.84 0.84 0.77</td>
<td>100</td>
<td>0.71 0.67 0.65</td>
</tr>
</tbody>
</table>

Cost Minimization

For the results of cost optimization, it is again interesting to compare the homogenous S500 and S700 solutions with the S355 case. Also, it is interesting to see, why bridge cross-sections...
I-beam: weight minimization

**RESULTS OF OPTIMIZATION**

Both the weight minimization and minimum cost problems were solved by the particle swarm algorithm (PSO) (Kennedy and Eberhart, 1995; Poli et al., 2007). In the literature, many possibilities regarding the details of the algorithm are available. In this study, an implementation of the PSO method was produced, with chosen constraint handling mechanism, velocity update rules with inertia term, craziness effect and elite particle. Furthermore, whenever the best feasible solution was updated, a neighborhood search was performed, i.e. better solutions were searched in a neighborhood of the solution. Detailed description of the algorithm is beyond the scope of this paper.

Three spans of 6m, 8m, and 10m were considered with three different loads, \( q = 20 \), \( q = 60 \), and \( q = 100 \). For the three available steel grades, S355, S500, and S700, altogether 14 combinations could be formed for each span and load. The only restriction was that the grade of the web cannot be greater than the grade of either of the flanges.

In each case, the design values of the bending moment and shear force are:

\[
M_{Ed} = \frac{1}{2}qL^2
\]

\[
V_{Ed} = \frac{1}{2}qL
\]

(24)

**Weight Minimization**

As a first step, it is interesting to compare the homogenous S500 and S700 cross-sections with the homogenous S355 profile, which works as the reference case. In Table 2, the ratios of the minimum weights of S500 to S355 and S700 to S355 are shown for different loads and spans. It can be seen that for the lowest load, \( q = 20 \), only marginal weights are achieved by HSS. This is partly explained by the allowable plate dimensions, that are not more favourable to HSS. On the other hand, the HSS solutions are mostly restricted by the displacement constraint where the higher strength does not play any role. For the S355 solution, the moment resistance constraint is dominant, even though the utilization ratio of the displacement constraint is also more than 90%.

For higher loads, the weight savings provided by the higher strength gets more significant. For the intermediate load \( q = 60 \), S500 gives a saving of about 15%, whereas S700 reduces the weight by about 25%. For the largest load, and largest span, the weight reductions are 23% for S500 and 35% for S700.

**Table 2: Results of weight minimization.**

The numbers are the ratios \( W^{\ast}_{500}/W^{\ast}_{355} \), and \( W^{\ast}_{700}/W^{\ast}_{355} \), where \( W^{\ast}_{fy} \) is the minimum weight of the homogenous cross-section with yield strength \( f_{fy} \).

<table>
<thead>
<tr>
<th></th>
<th>Span (m)</th>
<th></th>
<th>Span (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>6</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>20</td>
<td>0.98</td>
<td>0.97</td>
<td>0.90</td>
</tr>
<tr>
<td>60</td>
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<td>0.84</td>
<td>0.84</td>
</tr>
<tr>
<td>100</td>
<td>0.84</td>
<td>0.84</td>
<td>0.77</td>
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<tr>
<td></td>
<td>6</td>
<td>8</td>
<td>10</td>
</tr>
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<td>0.90</td>
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<td>0.76</td>
<td>0.74</td>
<td>0.73</td>
</tr>
<tr>
<td>100</td>
<td>0.71</td>
<td>0.67</td>
<td>0.65</td>
</tr>
</tbody>
</table>

*2-23%*

*2-35%*
**I-beam: cost minimization**

Table 3: Results of cost minimization.

<table>
<thead>
<tr>
<th>Load</th>
<th>S500 Span (m)</th>
<th>S700 Span (m)</th>
<th>Best Span (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6  8   10</td>
<td>6  8   10</td>
<td>6  8   10</td>
</tr>
<tr>
<td>20</td>
<td>1.15  1.14  1.10</td>
<td>20  1.26  1.25  1.22</td>
<td>20 1  1  0.99</td>
</tr>
<tr>
<td>60</td>
<td>1.06  1.03  1.01</td>
<td>60  1.10  1.06  1.03</td>
<td>60  0.95  0.93  0.90</td>
</tr>
<tr>
<td>100</td>
<td>1.04  1.04  0.94</td>
<td>100  1.04  0.96  0.94</td>
<td>100  0.93  0.91  0.90</td>
</tr>
</tbody>
</table>

Performing in cost optimization. In Table 3 the relative cost optima of S500, S700 and the best solution compared to S355 are given. It can be seen that HSS solutions become beneficial only for the largest load. In most cases, the material and fabrication costs of HSS are too high compared with S355.

For the lowest load, the S355 solution is the most economical, except for the largest span. Then, the solution with both flanges of S500 and the web of S355 is more economical. Within increased load, the hybrid cross-sections start to have a positive effect on the minimum cost. The cost savings vary from 5% to 10%. In all cases, the top flange is made of S700. The web is S355, except for the largest load and the largest span. Then it is S500. The bottom flange is of S700, except for the case $q=60/\lambda=6$, where it is of S355.

The cost distribution of the minimum cost solution is shown in Figure 2. It can be seen that the material cost is 50% of the total cost. Erecting cost plays an important role with a 16% share. Beam welding and painting are also relatively important, with 11% share each. Sawing, blasting, and transport contribute very little to the total cost.

| Material | 50% |
| Blasting | 2% |
| Cutting | 7% |
| Beam Welding | 11% |
| Painting | 11% |
| Erecting | 16% |
| Transport | < 1% |
| Sawing | 2% |

Discussion

In the above, the criterion values of the solutions were investigated. It is also interesting to study the actual designs that lead to the optimum solutions, i.e. of concern to the design space.

A common feature of the optimum design is that the web width is kept relatively low. The maximum flange width among the minimum weight solutions is 210 mm. Out of 126 cases, 83 solutions have flange width of 100 mm, i.e. the minimum value. Similarly, the thickness of the web is kept close to the minimum value of 5 mm. The maximum web thickness appearing in the...
I-beam: cost minimization

<table>
<thead>
<tr>
<th>S500</th>
<th>Span (m)</th>
<th>S700</th>
<th>Span (m)</th>
<th>Best</th>
<th>Span (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Load</td>
<td>6</td>
<td>8</td>
<td>10</td>
<td>Load</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>1.15</td>
<td>1.14</td>
<td>1.10</td>
<td>20</td>
</tr>
<tr>
<td>60</td>
<td></td>
<td>1.06</td>
<td>1.03</td>
<td>1.01</td>
<td>60</td>
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<td></td>
<td>1.04</td>
<td>1.04</td>
<td>0.94</td>
<td>100</td>
</tr>
</tbody>
</table>

Material: 50%
Blasting: 2%
Cutting: 7%
Beam Welding: 11%
Painting: 11%
Erecting: 16%
Transport: < 1%
Sawing: 2%

Figure 2: Cost distribution of the minimum cost beam.

Discussion

In the above, the criterion values of the solutions were investigated. It is also interesting to study the actual designs that lead to the optimum solutions, i.e., of interest in the design space.

A common feature of the optimum designs is that the width of the flanges is relatively low.

The maximum flange width among the minimum weight solutions is 210 mm. Out of 126 cases, 83 solutions have flange width of 100 mm, i.e., the minimum value. Similarly, the thickness of the web is kept close to the minimum value of 5 mm. The maximum web thickness appearing in the case is 10.24 mm. Out of 126 cases, 59 solutions have web thickness of 5 mm, i.e., the minimum value.
WQ-beam: weight minimization

### Table 3. Numbering of steel grade combinations.

<table>
<thead>
<tr>
<th>Load [kN/m]</th>
<th>S500</th>
<th>S700</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>13</td>
<td>5</td>
</tr>
<tr>
<td>100</td>
<td>53</td>
<td>5</td>
</tr>
<tr>
<td>140</td>
<td>53</td>
<td>5</td>
</tr>
</tbody>
</table>

### Table 4. Minimum weights of S500 and S700 beams relative to S355.

<table>
<thead>
<tr>
<th>Load [kN/m]</th>
<th>S500</th>
<th>S700</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>0.93</td>
<td>0.90</td>
</tr>
<tr>
<td>100</td>
<td>0.89</td>
<td>0.85</td>
</tr>
<tr>
<td>140</td>
<td>0.86</td>
<td>0.86</td>
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</tbody>
</table>

### 2.1 Weight Minimization

An anticipated result of weight minimization is that the homogeneous S700 provides the lightest structure. Then, it is interesting to compare the homogeneous S500 and S700 cross-sections with the homogeneous S355 profile, which works as the reference case. In Table 4, the ratios of the minimum weights of S500 to S355 and S700 to S355 are shown for different loads and spans. It can be seen that the S500 is able to achieve 7–15% weight reduction, whereas 12–25% savings can be obtained by S700. For both high strength grades, the tendency is that more material can be saved as the span and load are increased. However, for $q = 140$ kN/m and $L = 8$ m, the savings are less than for the lower loads and spans. This is due to the displacement constraint that becomes dominant. In the other cases, the moment resistance of the cross-section and the resistance of the lip of the bottom flange are the most active constraints.

In all but one of the 126 minimum weight solutions, the web thickness is assigned the minimum allowable value (5.0 mm). Consequently, the web is most often included. The compression flange varies more with the tendency of being 1 or 2 for larger spans and loads. For the optimum thickness of the bottom flange, both the moment resistance of the cross-section and of the lip are determining factors.

### 2.2 Cost Minimization

The results of cost minimization are summarized in Table 5, where the ratios of the optimized S500 and S700 cross-sections to the optimum S355 designs are shown. Furthermore, the ratios of the best steel grade combination to S355 are given. The numbers of the best combinations as per Table 3 are given in parenthesis. It can be seen that the homogeneous HSS cross-sections do not provide more economical solutions than S355. For S500, the beams are 11–22% more expensive, whereas S700 yields 19–35% more expensive designs. On the other hand, hybrid cross-sections are able to provide cost savings to S355, although only up to 4%. Typically several hybrid solutions give nearly equal costs. For all span/load-combinations, the web is of S355. The grades of the flanges vary substantially depending on the span and load, and there does not seem to be a straightforward rule for selecting the correct optimum flange grades for given span and load. Both S500 and S700 appear in the minimum cost solutions varyingly in both flanges.

The cost distribution of the minimum cost solution for $q = 100$ kN/m, $L = 6$ m is shown in Fig. 2a, and the corresponding cross-section is depicted in Fig. 2b. The cost distribution is similar throughout the solutions. Material cost is 60% of the total cost. Welding and straightening costs constitute 14% and...
WQ-beam: weight minimization

Table 3. Numbering of steel grade combinations.

Table 4. Minimum weights of S500 and S700 beams relative to S355.

<table>
<thead>
<tr>
<th>S500 Load [kN/m]</th>
<th>Span [m] 5</th>
<th>6</th>
<th>8</th>
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</thead>
<tbody>
<tr>
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<td>0.93</td>
<td>0.92</td>
<td>0.90</td>
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<tr>
<td>100</td>
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<td>0.85</td>
</tr>
<tr>
<td>140</td>
<td>0.86</td>
<td>0.85</td>
<td>0.86</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>S700 Load [kN/m]</th>
<th>Span [m] 5</th>
<th>6</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>0.88</td>
<td>0.87</td>
<td>0.83</td>
</tr>
<tr>
<td>100</td>
<td>0.83</td>
<td>0.78</td>
<td>0.80</td>
</tr>
<tr>
<td>140</td>
<td>0.77</td>
<td>0.75</td>
<td>0.86</td>
</tr>
</tbody>
</table>

7-15%
WQ-beam: weight minimization

Table 3. Numbering of steel grade combinations.

<table>
<thead>
<tr>
<th>Load [kN/m]</th>
<th>S500 Span [m]</th>
<th>5</th>
<th>6</th>
<th>8</th>
<th>S700 Span [m]</th>
<th>5</th>
<th>6</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td></td>
<td>0.93</td>
<td>0.92</td>
<td>0.90</td>
<td>60</td>
<td>0.88</td>
<td>0.87</td>
<td>0.83</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>0.89</td>
<td>0.88</td>
<td>0.85</td>
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<td>0.83</td>
<td>0.78</td>
<td>0.80</td>
</tr>
<tr>
<td>140</td>
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<td>0.86</td>
<td>0.85</td>
<td>0.86</td>
<td>140</td>
<td>0.77</td>
<td>0.75</td>
<td>0.86</td>
</tr>
</tbody>
</table>

7-15% 12-25%

Table 4. Minimum weights of S500 and S700 beams relative to S355.

2.1 Weight Minimization
An anticipated result of weight minimization is that the homogeneous S700 provides the lightest structure. Then, it is interesting to compare the homogeneous S500 and S700 cross-sections with the homogeneous S355 profile, which works as the reference case. In Table 4, the ratio of the minimum weights of S500 to S355 and S700 to S355 are shown for different loads and spans. It can be seen that the S500 is able to achieve 7–15% weight reduction, whereas 12–25% savings can be obtained by S700. For both high strength grades, the tendency is that more material can be saved as the span and load are increased. However, for \( q = 140 \text{kN/m} \) and \( L = 8 \text{m} \), the savings are less than for the lower loads and spans. This due to the displacement constraint that becomes dominant. In the other cases, the moment resistance of the cross-section and the resistance of the lip of the bottom flange are the most active constraints.

In all but one of the 126 minimum weight solutions, the web thickness is assigned the minimum allowable value (5.0 mm). Consequently, the web is most often included. The compression flange varies more with the tendency of being 1 or 2 for larger spans and loads. For the optimum thickness of the bottom flange, both the moment resistance of the cross-section and of the lip are determining factors.

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The results of cost minimization are summarized in Table 5, where the ratio of the optimized S500 and S700 cross-sections to the optimum S355 designs are shown. Furthermore, the ratios of the best steel grade combination to S355 are given. The numbers of the best combinations as per Table 3 are given in parenthesis. It can be seen that the homogeneous HSS cross-sections do not provide more economical solutions than S355. For S500, the beams are 11–22% more expensive, whereas S700 yields 19–35% more expensive designs. On the other hand, hybrid cross-sections are able to provide cost savings to S355, although only up to 4%. Typically several hybrid solutions give nearly equal costs. For all span/load-combinations, the web is of S355. The grades of the flanges vary substantially depending on the span and load, and there does not seem to be a straightforward rule for selecting the correct optimum flange grades for given span and load. Both S500 and S700 appear in the minimum cost solutions varyingly in both flanges.

The cost distribution of the minimum cost solution for \( q = 100 \text{kN/m}, L = 6 \text{m} \) is shown in Fig. 2a, and the corresponding cross-section is depicted in Fig. 2b. The cost distribution is similar throughout the solutions. Material cost is 60% of the total cost. Welding and grinding cost constitute 14%...
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### Table 4: Minimum weights of S500 and S700 beams relative to S355

<table>
<thead>
<tr>
<th>Load [kN/m]</th>
<th>Span [m]</th>
<th></th>
<th>Load [kN/m]</th>
<th>Span [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>1.22</td>
<td>1.22</td>
<td>1.19</td>
<td>1.35</td>
</tr>
<tr>
<td>100</td>
<td>1.18</td>
<td>1.15</td>
<td>1.12</td>
<td>1.29</td>
</tr>
<tr>
<td>140</td>
<td>1.14</td>
<td>1.12</td>
<td>1.11</td>
<td>1.22</td>
</tr>
</tbody>
</table>

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WQ-beam: cost minimization

Table 3. Numbering of steel grade combinations.

<table>
<thead>
<tr>
<th>S500 Load [kN/m]</th>
<th>Span [m]</th>
<th>S700 Load [kN/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>1.22</td>
<td>60</td>
</tr>
<tr>
<td>100</td>
<td>1.18</td>
<td>100</td>
</tr>
<tr>
<td>140</td>
<td>1.14</td>
<td>140</td>
</tr>
</tbody>
</table>

+11-22%

Table 4. Minimum weights of S500 and S700 beams relative to S355.

<table>
<thead>
<tr>
<th>S500 Span [m]</th>
<th>S700 Span [m]</th>
<th>Load [kN/m]</th>
</tr>
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<tbody>
<tr>
<td>5</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>60</td>
<td>0.93</td>
<td>0.92</td>
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<tr>
<td>100</td>
<td>0.89</td>
<td>0.88</td>
</tr>
<tr>
<td>140</td>
<td>0.86</td>
<td>0.85</td>
</tr>
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</table>

Table 5. Minimum costs of S500 and S700, and the best steel grade combination relative to S355.

<table>
<thead>
<tr>
<th>S500 Span [m]</th>
<th>S700 Span [m]</th>
<th>Best Span [m]</th>
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<tbody>
<tr>
<td>5</td>
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<tr>
<td>60</td>
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<td>1.19</td>
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<td>1.14</td>
<td>1.11</td>
</tr>
</tbody>
</table>

+11-22%
2.1 Weight Minimization

An anticipated result of weight minimization is that the homogeneous S700 provides the lightest structure. Then, it is interesting to compare the homogeneous S500 and S700 cross-sections with the homogeneous S355 profile, which works as the reference case.

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In all but one of the 126 minimum weight solutions, the web thickness is assigned the minimum allowable value (5.0 mm). Consequently, the web is most often included. The compression flange varies more with the tendency of being 1 or 2 for larger spans and loads. For the optimum thickness of the bottom flange, both the moment resistance of the cross-section and of the lip are determining factors.

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The cost distribution of the minimum cost solution for $q=100\text{kN/m}$, $L=6\text{m}$ is shown in Fig. 2a, and the corresponding cross-section is depicted in Fig. 2b. The cost distribution is similar throughout the solutions. Material cost is 60% of the total cost. Welding and re-recting cost constitute 14% and

<table>
<thead>
<tr>
<th>S500 Load [kN/m]</th>
<th>Span [m]</th>
<th>S700 Load [kN/m]</th>
<th>Span [m]</th>
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</thead>
<tbody>
<tr>
<td>60</td>
<td>5  1.22</td>
<td>1.35</td>
<td>5  1.35</td>
</tr>
<tr>
<td>100</td>
<td>6  1.22</td>
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<td>6  1.35</td>
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<tr>
<td>140</td>
<td>8  1.19</td>
<td>1.30</td>
<td>8  1.30</td>
</tr>
</tbody>
</table>

+11-22%           +19-35%
WQ-beam: cost minimization

Table 3. Numbering of steel grade combinations.

<table>
<thead>
<tr>
<th>Best Load [kN/m]</th>
<th>Span [m]</th>
<th>5</th>
<th>6</th>
<th>8</th>
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</thead>
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<tr>
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<td>1.00 (1)</td>
<td>1.00 (7)</td>
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<td>0.99 (11)</td>
<td>0.97 (4)</td>
<td>0.96 (9)</td>
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</table>

Table 4. Minimum weights of S500 and S700 beams relative to S355.

<table>
<thead>
<tr>
<th>Load [kN/m]</th>
<th>S500 Span [m] 5</th>
<th>S500 Span [m] 6</th>
<th>S500 Span [m] 8</th>
<th>S700 Span [m] 5</th>
<th>S700 Span [m] 6</th>
<th>S700 Span [m] 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>0.93</td>
<td>0.92</td>
<td>0.90</td>
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<td>0.87</td>
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<tr>
<td>140</td>
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</tr>
</tbody>
</table>

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tubular trusses
The trusses considered are simply supported single-span roof trusses. The design domain is shown in Figure 2.1. The span of the truss is varied such that \( L = 24 \text{m} \) or \( L = 36 \text{m} \). For both spans, the height \( h \) can take the values \( h = L/10 \) and \( h = L/20 \). Thus, the geometry of the design domain implies 4 different cases.

For each variation of design domain geometry, two cross-section scenarios are considered:

1. Chords are HEA/HEB (S460), and the braces are CHS (S355);
2. Chords are SHS (S420), and the braces are SHS (S355).

The following loads are employed:

- Dead load of roofing \( 0.5 \text{kN/m}^2 \)
- Self-weight of truss \( 0.16 \text{kN/m}^2 \)
- Snow \( 0.8 \times 2.5 \text{kN/m}^2 = 2.0 \text{kN/m}^2 \)

The distance between trusses is \( c/c = 6 \text{m} \).

The design load is determined based on the Swedish National Annex of (EN 1990 2002):

\[
\begin{align*}
\gamma_d \cdot 1.35 G_{kj}, & \\sup \otimes \gamma_d \cdot 1.5 Q_k, \\
\gamma_d \cdot 0.89 \times 1.35 G_{kj}, & \\sup \otimes \gamma_d \cdot 1.5 Q_k,
\end{align*}
\]

Comparative Evaluation of Steel Profiles in Roof Trusses

- Minimize cost and weight (separately)
- Steel grades: S355, S500, S700, S960
shape optimization

- Topology fixed (KT- and K-truss)
- Truss height and node locations can be varied
- Additionally, optimum member profiles are determined
- Particle Swarm Optimization algorithm employed
### Cost Factors

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>S355</th>
<th>S500</th>
<th>S700</th>
<th>S960</th>
</tr>
</thead>
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<tr>
<td>Material</td>
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<td>1.6</td>
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<tr>
<td>Sawing</td>
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<td>1.3</td>
<td>1.5</td>
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<tr>
<td>Welding</td>
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<td>1.25</td>
<td>1.5</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Material cost of tubular products (S355): 0.8 €/kg
results of optimization

- **S355/S355**: 100% Cost, 100% Weight
- **S500/S500**: 92% Cost, 74% Weight
- **S700/S700**: 86% Cost, 60% Weight
- **S960/S960**: 92% Cost, 50% Weight
results of optimization

Cost results of optimization

- S355/S355: 100%
- S500/S500: 92%
- S500/S355: 87%
- S700/S700: 86%
- S700/S355: 79%
- S700/S500: 86%
- S960/S960: 92%
- S960/S355: 86%
- S960/S500: 95%
- S960/S700: 89%
results of optimization

[S355/S355: 100%]
[S500/S500: 92%]
[S500/S355: 87%]
[S700/S700: 86%]
[S700/S355: 79%]
[S700/S500: 86%]
[S960/S960: 92%]
[S960/S355: 86%]
[S960/S500: 95%]
[S960/S700: 89%]
results of optimization

Weight

- S355/S355: 100%
- S500/S500: 74%
- S500/S355: 76%
- S700/S700: 60%
- S700/S355: 62%
- S700/S500: 64%
- S960/S960: 50%
- S960/S355: 58%
- S960/S500: 58%
- S960/S700: 52%
results of optimization

Weight results of optimization
minimum cost trusses

- S355
- S500
- S700
- S960
- S700/S355

Cost optimum

-8%
-14%
-8%
-8%
-21%
conclusions

• Designers hold the keys for utilisation of HSS in construction — need suitable tools

• Hybrid solutions are attractive

• With improving manufacturing technologies, even more savings can be obtained

• For finding the most economical designs, cost data from steel producers and workshops should be available