OTTIMIZZAZIONE DELLA CONNESSIONE PENDINO -ARCO RIGUARDO ALLA FATICA NEL CASO DI ARCO IN PROFILO LAMINATO AD H –ANALISI NUMERICHE E REALIZZATIVE

OPTIMIZATION OF GUSSET PLATE CONNECTION TO H ROLLED SECTION FOR FATIGUE –NUMERICAL ANALYSIS AND FABRICATION CONSIDERATIONS

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ABSTRACT

The paper investigates the detailing of gusset plate serving as connection of the hanger to an arch member in form of a H-shaped rolled section in the frame of a tied-arch bridge. The driver of the investigation is the fatigue resistance, critical criterion for this element. Since rolled sections used for this application belong to the same geometrical family it is possible to define a common geometric basis. At first a variety of geometric shapes have been considered and analysed by means of FEM numerical simulations. This preliminary analysis delivers a rating in term of sensitivity to fatigue resistance, with best grades for the shapes with lower the stress peaks. Beside the rating based on structural performance, a second rating has been proposed based on easy of execution. The combined results from these two ratings have permitted to identify the most suitable gusset shape. This shape has been afterwards investigated in term of hot-spot stress peaks, considering the influence of the different hanger – arch inclination. This study leads to a proposal for the most appropriate geometric detailing for the gusset plate in the case of the arch as H- rolled sections with low stress peak concentration and at the same time a feasible fabrication process.

SOMMARIO

La memoria si concentra sul dettaglio della piastre di collegamento tra pendini e l’arco metallico di un ponte tipo bowstring per il caso specifico di un arco in profile laminato. L’aspetto che ne determina la performance é la resistenza allo stato limite di fatica. Poiché le sezioni laminate

utilizzate per questa applicazione appartengono alla stessa famiglia geometrica (HD400) è possibile definire generica per lo studio. Dapprima si sono proposte una varietà di forme geometriche che sono state analizzate con modelli FEM. Questa analisi preliminare fornisce una valutazione in termini di sensibilità alla resistenza alla fatica, selezionando le forme con picchi di stress più bassi. Oltre al rating basato sulle prestazioni strutturali, è stato proposto un secondo rating basato sulla facilità di esecuzione in officina del dettaglio. I risultati combinati di queste due valutazioni hanno permesso di identificare la forma del collegamento più adatta. Questa forma è stata successivamente studiata in termini di picchi di stress hot-spot, considerando l'influenza della diversa inclinazione del gancio - arco. Questo studio propone in conclusione una geometria unica della piastre adeguata alle sezioni laminate HD400, unendo una concentrazione minima di stress locali ma allo stesso tempo un processo di fabbricazione fattibile.

1 INTRODUCTION

The tied-Arch bridges are classical typology which is lately experiencing a renaissance thanks to its valuable aesthetics and structural efficiency. The arch develops above the horizonal deck which carries the lane and is suspended to the arch by means of hangers. Various hanger arrangements are possible [3]. The specificity lies in the fact that the arch is connected at its end in the deck itself (which acts like a tie) to form a self-equilibrated structure. This implies that when it is subjected to vertical loads it transmits only vertical reactions at supports, differently from other arched structures. This investigation focuses on hanger-arch connection for the specific case of arch rib formed by a H-shaped rolled section (see Figure 1**Fig**).
High strength rolled sections are an efficient solution for the realization for spans between 50m and 120m when the hanger spacing has an average distance between 3m and 5m [5]. In this span range, hangers are often realized by solid bars with threaded connections at their ends. Producers provide standardized solutions for the pinned end connection as well as for the couple turnbuckle which ensure the prestressing (e.g. [4]). The installation is easy, and for lengths up to 20m they are an efficient solution. Arch out of rolled sections linked with hangers out of solid threaded bars both in S460 grades are consistent choices which make this bridge typology technically accessible and economically convenient. More than twenty bridges with this arch rib type were built [5].

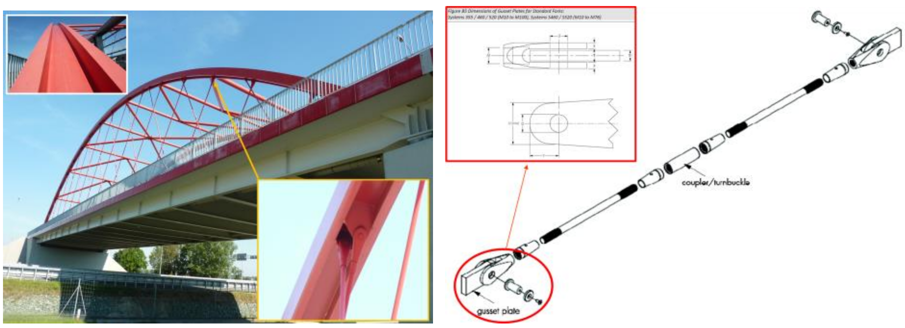


Fig. 1. WD-431 on S5 near Rawicz (2008) [5], Solid threaded bar with gusset plate [4]

2 SELECTION OF GUSSET PLATE FORM

2.1 Discussion of existing solutions

The hanger-to-arch connection is not a new topic and there is experience and technical literature. Several technical solutions are possible depending on the structural design as well as on the local construction practice. The material and the maintenance of the axis are important to ensure the correct behaviour as pinned connection along the life of the structure. Independently from the solution used for the hanger, it will transfer the loads to a gusset plate which is fixed (usually welded) to the arch. When using compact H-rolled shapes there are some specific characteristics different from the common welded plates box girders:

1) Fixing the gusset plate to the H-rolled shape is generally easier than for box girders. For example, the common detail in Germany foresees the gusset plate interrupting the longitudinal bottom plate of the box to reach the core of the arch cross-section. This interruption requires the realization of one full penetration weld of the bottom flange at its crossing with the gusset plate, creating a discontinuity for fatigue and a considerable through thickness solicitation in the gusset plate.

2) In open H-sections all the welds are visible and inspectable along the bridge service life; hidden welded detail inside the box girder is avoided.

3) The principal constraint is that dimensions of the inner chamber of the profile are fixed and therefore a careful geometric check is needed to ensure the connection feasibility.

2.2 Shapes considered for the gusset plates

Although some shapes have been already proposed and used, the first step has been to make a step back and considering 14 possible shapes (see Figure 2) to select the one which is the more adapted. In this first stage the gusset plates are perpendicular to the axis of the arch (corresponding to a radial hanger arrangement); the influence of the inclination will be considered at a later stage only for the selected shape. It must be commented that some forms (e.g. A, B, C) have been selected as reference and it is clear that are not of practical interest. The shapes which can be found in real projects and literature are similar to E, F, G, H, I, J forms.

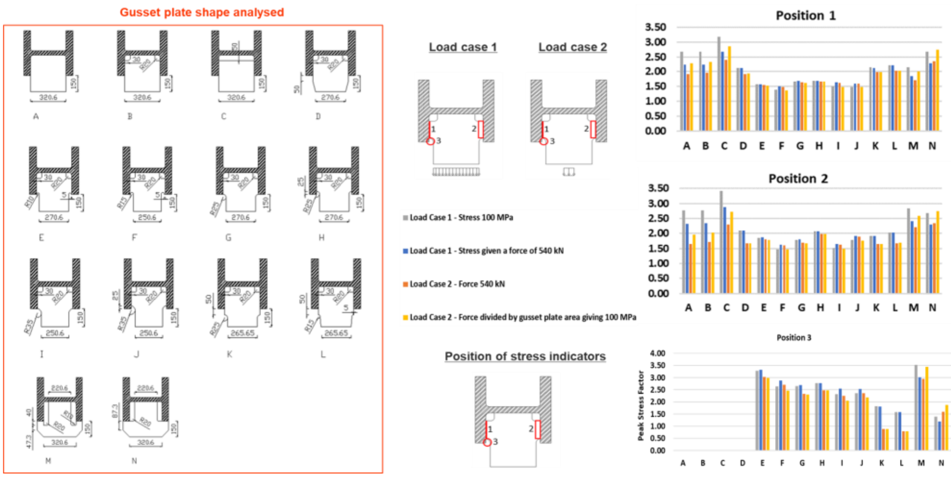


Fig. 2. Gusset plate shapes analysed; load case applied; position of stress indicators and results

For the arch sections it is common to use rolled sections belonging to the HD400 family. They present the same internal dimensions (net height of the web, internal clear distance between the flanges), but thickness of flange and web vary. In particular it can be recalled that the internal clear distance between the flanges is fixed to 320.6mm. This fact allows to conclude that the same gusset plate geometry can be used for the whole HD400 family, an important advantage since the design can be simplified. The thickness of the gusset plate in this study is fixed to 25mm: it may seem not very thick, but in fact the capacity of this gusset plate under pure traction is around two hundred tons and may be enough for several applications. The gusset plates will be welded to the arch by means of full penetration welding; in fact, due to the requirements imposed by fatigue design, the use of fillet weld connections is not advised for this detail.
The thickness of the gusset plate is not varied as the study focuses on the optimal shape and not on the notch stress factor. Even with this limitation, given the fact that for general applications the outer dimensions will be constant and only thickness will change authors believe that the conclusions can be taken as coherent for the whole section family and in a gusset plate thickness range of 12.5mm up to 50mm. Authors nevertheless clarify that the numerical results of this study are used to make a qualitative selection of the geometry of the gusset plate and shall not be used outside this context.

2.3 Model used for preliminary analysis

The evaluation of the structural behaviour has been made considering FEA analysis using the ABAQUS® software. The different simulations that have been made use a part that comprised both members (beam and gusset plate) using C3D8R elements. The weld itself is not modelled and the two parts have been completely merged since full penetration welding is supposed to be used. The model is a simply supported linear elastic beam of 4m, with a curvature radius of 10.1m about the weak axis. Two different load cases are considered:

1) Load case 1: Full area of the gusset plate subjected to a nominal tension at 100MPa. This load case simulates the case of a longer gusset plate where the forces are distributed homogeneously along its section.
2) Load case 2: Force of 540kN on a length of 60 mm, at the centre line of the gusset plate. This second load case simulates the case of a short gusset plate where the stresses remain concentrated in the central part. The force of 540kN has been calculated as the equivalent force developed at the previous point.

Important is to note that the force was applied without eccentricity or out of plane bending. Relevant results are extracted for three specific zones (see Figure 2):
1) Transition line between the gusset plate and the beam flange. In this zone the membrane forces in the plane of the gusset plate become shear stresses in the arch, namely in the flanges which are the part of the sections who carry most of the shear about weak axis.
2) Area of the gusset plate adjacent to the beam flange (so beside the area described in point 1).
3) Peak linked with the geometric kerf of the gusset plate connection to the arch.
It is important to relate that in the frame of this preliminary analysis, the FEM model stress peak output is used and not the formula to calculate the hot-spot stress proposed in [2] (for this reason, in this paper the definition “stress peak” is used instead of “hot-spot stress”). This is due to the large number of models with different geometries and several locations considered where stress peaks appear. Applying the rule in [2] for this preliminary study would have required a considerable additional effort to create a regular mesh and extract output to apply the calculation.
Authors consider that the qualitative assessment based on stress peaks is sufficiently reliable for a preliminary analysis. For a sufficient fine mesh it is reasonable to assume that a shape having an higher stress peak will also have an higher hot spot stress. Since this preliminary analysis uses the

output of the FEM model, the mesh size plays an important role and therefore a benchmark study was done. The case of an “infinite” plate with a hole with known theoretical solution was taken. Figure 3 shows the ratio of the stress peak of the numerical simulation divided by the analytical solution in function of *r* / *d* (where *r* is the radius of the hole, and *d* the reference dimension of the element). It can be observed that for the given element a ratio larger than 8…10 is advisable. A comparable approach has been found in the literature (e.g. [6]). The mesh was therefore adapted based on this parameter (see Figure 3).

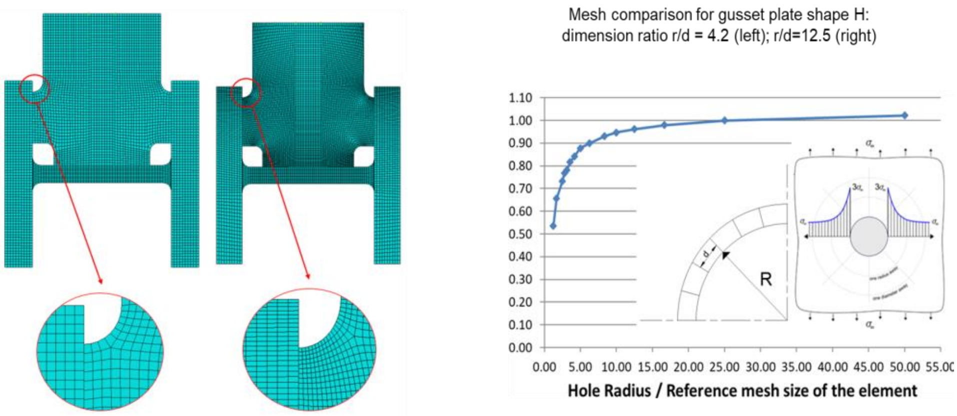


Fig. 3. Mesh comparison for gusset plate shape H: dimension ratio r/d = 4.2 (left); r/d=12.5 (right)

2.4 Considerations about stress peaks

The numerical simulations have been run for the set of 14 gusset plate shapes considering the two proposed load cases.As it could be expected gusset plate shape A to C are associated with high stress peak and are not of great technical interest. For positions 1 and 2 (Fig. 6) it´s possible to conclude that the stress peak is smaller for forms that have a radius change in the connection with the beam flanges (solutions E to J). The cut radius allows for a smoother transition of stresses, avoiding peak stress concentrations in the edges of the gusset plates connecting to the beam.

Solutions F and I present the smaller stress peak for position 1 (1.36 and 1.48 for Load case 2) and shapes that have the radius matching the flange edge (for example G and I,) have lower concentrations according to their counterpart designs (H and J) for to position 2.

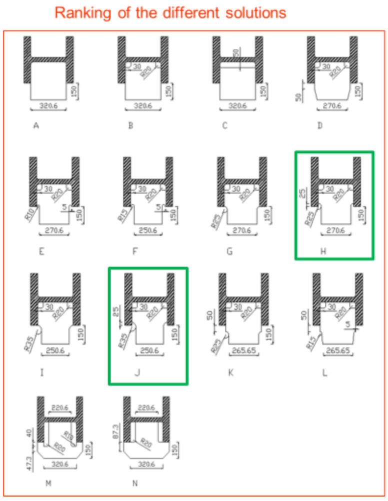
Regarding position 3, the stress concentration is smaller for solutions K and L (0.89 and 0.80 for Load case 2) since the transition radius is farther from the connection area between the gusset plate and beam flanges. It is important to note that solution N also shows good results in this case.

Comparing N and M, the stress values are smaller for N since the transition radius in the middle part of the gusset plate is made in a smother matter when compared to M.

Fig. 4. Example of considerations concerning the easiness of fabrication

2.5 Considerations about fabrication aspects

The different gusset plates showed in Figure 3 imply different levels of complexity in terms of piece preparation, tolerance for assembly, execution of welding as well as quality control. At this stage it shall be also considered that in some cases the gusset plate can have an angle and not be perpendicular to the beam axis itself or have some fabrication tolerances. For this reason, situation such as the one defined in Figure 4 are perfect for FEM modelling but are in fact extremely complicated to realize, when considering welding of thick parts. Based on the large industrial experience of the ArcelorMittal workshop, a ranking note has been proposed to assess the easiness of fabrication. The grades range from 1 to 5, with 1 being the most complex and 5 the easiest.



The total ranking is a note composed by two factors: the stress peak note and the fabrication effort:

$$\text{Ranking} = S_s + F_s$$

Ranking - Load Case 1									
Considering Position 1					Considering Position 2				
Design	Stress Pos.1	Score Stress (S_s)	Score Fab (F_s)	Ranking	Design	Stress Pos.1	Score Stress (S_s)	Score Fab (F_s)	Ranking
A	2.46	2.08	4.00	6.08	A	2.55	1.90	4.00	5.90
B	2.45	2.09	4.50	6.59	B	2.56	1.88	4.50	6.38
C	2.92	1.16	5.00	6.16	C	3.15	0.70	5.00	5.70
D	2.13	2.73	4.00	6.73	D	2.10	2.79	4.00	6.79
E	1.58	3.85	1.00	4.85	E	1.86	3.27	1.00	4.27
F	1.45	4.10	1.00	5.10	F	1.55	3.90	1.00	4.90
G	1.68	3.63	3.00	6.63	G	1.79	3.43	3.00	6.43
H	1.68	3.63	4.25	7.88	H	2.07	2.86	4.25	7.11
I	1.58	3.85	3.00	6.85	I	1.58	3.84	3.00	6.84
J	1.55	3.90	4.25	8.15	J	1.86	3.28	4.25	7.53
K	2.14	2.73	3.80	6.53	K	1.93	3.15	3.80	6.95
L	2.21	2.58	3.70	6.28	L	2.03	2.93	3.70	6.63
M	2.00	3.01	3.00	6.01	M	2.63	1.75	3.00	4.75
N	2.49	2.03	3.00	5.03	N	2.49	2.03	3.00	5.03
Ranking - Load Case 2									
Considering Position 1					Considering Position 2				
Design	Stress Pos.1	Score Stress (S_s)	Score Fab (F_s)	Ranking	Design	Stress Pos.1	Score Stress (S_s)	Score Fab (F_s)	Ranking
A	2.11	2.78	4.00	6.78	A	1.81	3.39	4.00	7.39
B	2.14	2.73	4.50	7.23	B	0.00	3.25	4.50	7.75
C	2.63	1.75	5.00	6.75	C	0.00	1.98	5.00	6.98
D	1.93	3.14	4.00	7.14	D	0.00	3.66	4.00	7.66
E	1.54	3.93	1.00	4.93	E	0.00	3.41	1.00	4.41
F	1.43	4.14	1.00	5.14	F	0.00	3.94	1.00	4.94
G	1.64	3.72	3.00	6.72	G	0.00	3.63	3.00	6.63
H	1.67	3.67	4.25	7.92	H	0.00	3.02	4.25	7.27
I	1.55	3.89	3.00	6.89	I	0.00	3.89	3.00	6.89
J	1.55	3.90	4.25	8.15	J	0.00	3.33	4.25	7.58
K	1.98	3.03	3.80	6.83	K	0.00	3.71	3.80	7.51
L	2.03	2.95	3.70	6.65	L	0.00	3.63	3.70	7.33
M	1.86	3.28	3.00	6.28	M	0.00	2.21	3.00	5.21
N	2.54	1.91	3.00	4.91	N	0.00	1.91	3.00	4.91

Ranking between load cases and points													
A	B	C	D	E	F	G	H	I	J	K	L	M	N
5.90	6.38	5.70	6.73	4.27	4.90	6.43	7.11	6.84	7.53	6.53	6.28	4.75	4.91

Fig. 5. Ranking of gusset plate shape: selected shape H and J

2.6 Ranking of the gusset shapes

The total ranking is composed by two components: Ranking = $S_s + F_s$, where S_s is the score obtained based on the stress peak and F_s is the grade for fabrication. The stress score is linked to the maximum value of peak stress obtained for a given shape between position 1 and position 2 (score given by linear interpolation with 1 having a 5 score, and 3 having a 1 score). Position 3 has been disregarded for this evaluation since it corresponds to a stress peak in the base material. The grade for fabrication has been explained in the previous chapter. The results of this ranking are showed in Fig. 6 for each load case and for position 1 and 2. The minimum amongst the 4 value is then the value which is considered for the final rating. The conclusion is that gusset plate forms H and J are the best. They are in fact quite similar, the only change being the fillet radius at the gusset plate – beam flange connection. The fabrication is quite the same, but shape J has in fact lower stress peaks since the radius is larger. Shape H on the other side has the relevant advantage to have a wider gusset plate (270mm instead of 250mm, +8%).

3 EFFECTS OF GUSSET PLATE INCLINATION

In tied-arch bridges with radial hanger arrangement the gusset plate is always perpendicular to the arch, constituting an important asset which simplifies both connection design as well as fabrication. In all other hanger arrangements (vertical, network or fan-shape), nevertheless the gusset plate is not perpendicular to the arch axis and is different at each connection. It is therefore important to analyse the effect of this inclination on the stress peaks. Numerical simulations have been made with an angle variation between 0º (gusset plate perpendicular to the arch axis) and 35º degrees, covering the main range of interest. Analyses have been made both with simply supported and fixed beam systems as well as with cantilever system. This latter has a bending moment shape which is less realistic, but since global bending is absent at load introduction point it permits to have only the local effects of gusset plates. Based on the previous selection, the geometry of gusset plate H is used but results can be reasonably extended to shape J.

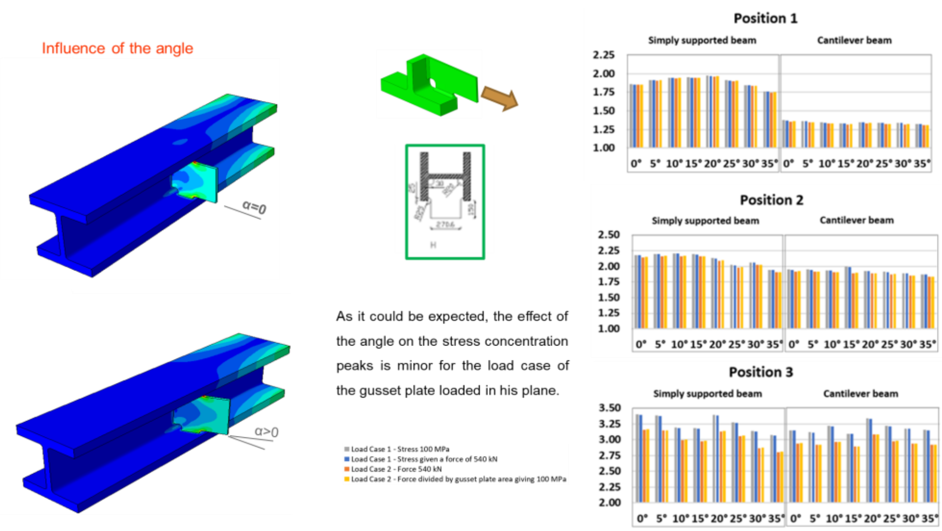


Fig. 6. Example of grey-scale photograph

As it can be expected the interaction between global and local stresses plays a remarkable role only in position 1; for position 2 and 3 the difference between the static system is not significative. It can be observed that the impact of the angle is moderate; in general, the most critical case is at around 20°, whereas at higher angles the stress peak does not tend to increase. In any case the difference remains in a range of 10%.

CONCLUSIONS

The results obtained in the numerical simulations presented in this paper have been used with the purpose to orientate the designer amongst different possibilities of gusset plates for application to H rolled sections. The shape advised is showed in Figure 7 and it is considered the best compromise. In the frame of a first estimation the notch stress factor in the base material of the gusset plate can be taken on the safe side as 3.4 (comparable with results in literature for, e.g. see Chart 5.10e of [1]). For the weld location between the gusset plate and the arch, the interaction of local effects with global stresses in correspondence of the weld shall be considered. The case of the gusset plate perpendicular to the arch axis is covered by the current standards; for other cases shall take safe assumptions or perform advanced analysis.

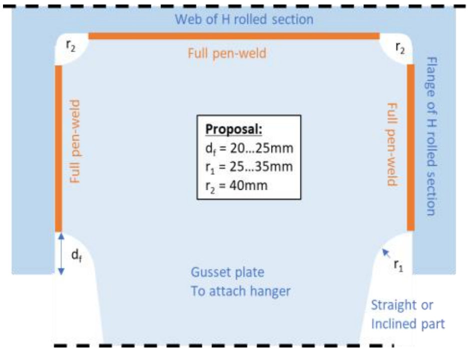


Fig. 7. Proposed shape of the gusset plate in correspondence of the H rolled shape connection

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KEYWORDS

Tied-Arch bridge, bowstring bridge, hanger connection, gusset plate