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IMPERFECTIONS IN STEEL PLATED STRUCTURES AND THEIR IMPACT ON ULTIMATE STRENGTH

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Abstract*. Initial imperfections in welded plated systems and web tolerances. Analysis of the effect of initial web curvatures on the ultimate strength of the whole girder, with the view to find out whether it is possible to avoid costly straightening of plate elements involved.*

1 THIN-WALLED CONSTRUCTION

Numberless are situations where an application of thin-walled construction is very advantageous. For example, in steel bridgework this is in the case of bridges with larger spans.

That is why a great attention has been internationally paid to research on post-buckled behaviour and ultimate strength of slender webs, flanges and other plate elements, the Czech research always striving to play a useful role in these activities.

However, there are also numerous cases where another approach is more economical. This results from the fact that the price of a steel structure is not only given by the price of the steel used but is also considerably affected by the cost of the fabrication of the structure. And in a good many situations it is the latter aspect that prevails; then it does not matter much that the structure in question is by a few tons heavier if this is compensated (and frequently outweighed) by substantially reduced fabrication costs.

2 WAYS TO ECONOMIC-FABRICATION CONSTRUCTION

The above objective can be achieved in two ways, viz. by means of (i) a simple and easily fabricated structural system, (ii) a reduction or a complete elimination of some costly fabrication procedures.

2.1 A simple structural system

In bridge construction this occurs with small and medium-span bridges, where a simple system, composed of a simple welded I-beam (without any longitudinal ribs and with as few transverse stiffeners as possible) made composite with a concrete slab is becoming very popular.

Then the amount of welding and other fabrication processes, and consequently also the fabrication costs, are very substantially reduced.

2.2 A reduction of some fabrication procedures

But the economic-fabrication approach is not only connected with the structural system chosen, but also with the way it is fabricated. And in this respect an important question ought to be asked, viz. should we straighten the plate elements (for example the webs of steel plate and box girders) of which the structural system is composed, which, as a result of the fabrication of the system (in particular as a result of the welding procedures used), always exhibit an initial curvature?

It is practically impossible to fabricate welded steel plated structures without their plate elements exhibiting initial curvatures. Therefore it is understandable that various standards require that this initial “dishing” be kept under control via prescribed tolerances and that in the case of need the magnitude of the initial curvature be reduced by straightening, usually heat straightening.

But is this really indispensable and desirable?

Of course, we are not the first to pose this question:

The problem was already dealt with some time ago by the Task Group “Tolerances in Steel Plated Structures”, sponsored b the IABSE, chaired by Prof. Ch. Massonnet [5], with the second author of this paper being a member of the Task Group. And the observations made during, and the conclusion drawn from, the activities of the Task Group are very much of interest even now.

It is true that discussions within the Task Group exhibited some differences of opinion. However, these differences notwithstanding, the Task Group tended to the opinion that heat straightening in steel plated structures is not desirable.

And the authors of this paper endorse the above stand point, the reasons being twofold:

(i) The procedure of straightening is rather costly (not only directly, but also due to blocking some space in the steel fabricator which can be used for other operations) and therefore would not be compatible with the aforesaid economic-fabrication strategy.

(ii) While it is understandable that the straightening of webs should be employed for aesthetical and psychological reasons, it is not certain that the actual stability behaviour of a girder with a straightened web is better than that of the original girder. To straighten the web of a girder by heat treatment only means that one initial imperfection (initial web curvature) is replaced by another initial imperfection (additional residual stresses induced by the heat treatment applied). The aforementioned Task Group also turned attention to another important fact; namely, while in the case of compressed plates (e.g. the compression flanges of steel box girder bridges) the influence of an initial curvature on load-carrying capacity can be significant (in ordinary cases even 20%), with webs subjected to combined shear and bending the same effect is (of course. when the initial dishing is not too large - and it should not be when the plated structure is fabricated in a good enough steel fabricator) much less important.

But is it really so?

If we desire to go as far as entirely to disregard the effect of unavoidable initial web curvatures, we must be certain that the influence of initial web “dishing” larger than usually adopted tolerances will not imperil the safety of steel plated girders.

And for this reason the authors have started an extensive investigation into the impact of various (but practically important) configurations and magnitudes of web initial curvature on the limit state of steel girders.

3 THE AUTHORS’ STUDY OF THE INFLUENCE OF THE INITIAL CURVATURE OF THE WEBS OF STEEL PLATE GIRDERS ON THE ULTIMATE LIMIT STATE OF THE GIRDER

3.1 Girders used in the analysis

The study was carried out on three types of plate girders. The first of them were test girders (Fig. 1) used by the second author of this contribution and M. Zörnerová in their numerous experiments on the “breathing” cumulative damage process and fatigue limit state of the webs of steel girders subjected to many times repeated combined shear and bending.

Like most girders tested now by the second writer and M. Zörnerová at the Institute of Theoretical and Applied Mechanics in Prague, they are fairly large, having a web 1000mm deep, so that their character is not far from that of ordinary girders. One of the experimental girders in the testing position is shown in Fig. 2.

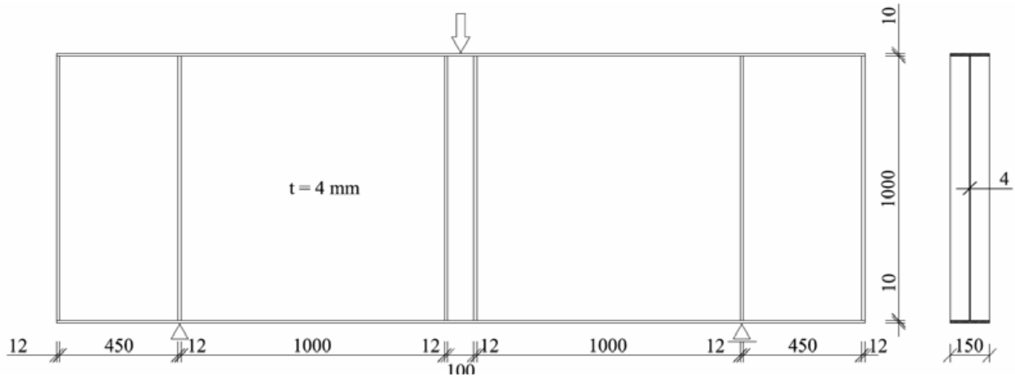

Figure 1: Test girder TG with α = 1.

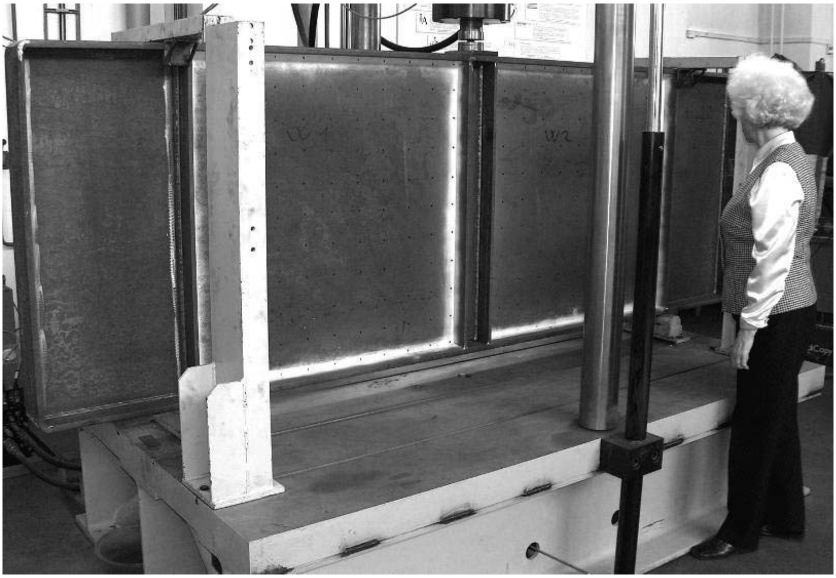

Figure 2: One of the Prague experimental girders in the testing position.

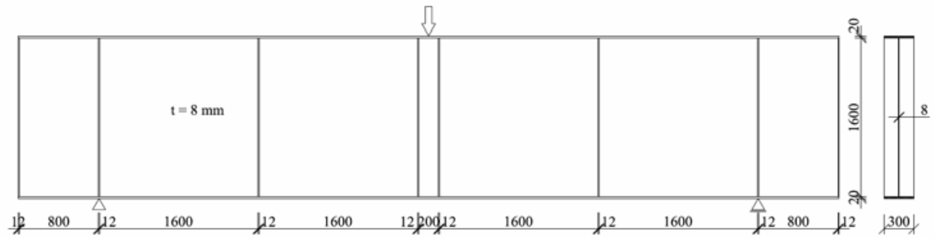

Figure 3: Larger girders used in the analysis.

All the girders were fabricated in the steel fabricator of Division 7 of the Company METROSTAV plc. (which is one of the best steel fabricators in the Czech Republic), using the same technological procedures as are applied there in the fabrication of ordinary steel bridges. It is important to note at this juncture that, compatibly with the problem treated in this paper, in the fabrication of the test girders no attempt was made to diminish (by heat treatment) the initial curvature of the web generated during the process of girder fabrication.

The shape and magnitude of the initial "dishing" of both of the web panels of all the test girders were very carefully measured and then their contour plots elaborated.

The shape of the initial curvature varied from girder to girder, this depending mostly on the regime of welding used, but usually exhibited one half-wave in the longitudinal direction and one or two half-waves in the transverse one. Their amplitudes were in the interval 2 - 11mm, i.e. $d/500$ - $d/91$, d being the depth of the web.

The advantage of using in the theoretical investigation the same girders as were employed in the Prague experimental analysis was in the possibility to verify the theoretically predicted ultimate loads by comparing them with their experimental counterparts, since in addition to "breathing" tests under repeated loading, part of the Prague girders were also tested statically, i.e. in the same regime as in our theoretical analysis.

The second type of girder is similar, but has longer web panels, so that their aspect ratio $\alpha = 2$.

Another part of the calculations were conducted on larger girders, viz. on those depicted in Fig. 3, various kinds of initial imperfections being again considered.

3.2 Theoretical apparatus applied in the analysis

The study of the effect of web initial curvature on the ultimate limit state of steel plate girders was based on an application of elasto-plastic large-deflection theory, the ANSYS program being used in the analysis [1].

The Euler method based on proportional loading in combination with the Newton-Raphson method was used. The girder was modelled, in a very minute manner, by means of a mesh of shell four-node elements SHELL 181. The girder symmetry and that of loading were made use of. The loading test is simulated by the incrementation of a loading step in the Euler method. The load-carrying capacity was determined as the loading rate at which the matrix of tangential toughness determinant Kt of the structure approaches zero with accuracy of 0.1 %. The incrementation run was decremented automatically. For steel grade S235, bilinear kinematic material hardening was supposed. Further on, it was assumed that the onset of plastification occurred when the Mises stress exceeded the yield stress.

At this juncture it should be mentioned that the theoretically predicted ultimate loads very well correlated (the difference being only a few p.) with their experimental counterparts. Thereby the reliability of the theoretical results was confirmed.

4 THE MAIN RESULTS OF, AND THE PRINCIPAL CONCLUSIONS DRAWN FROM, THE ANALYSIS

The main results of the authors' analysis are summed up in Tables 1-5. Table 1 is related to the Prague experimental girders with $\alpha = 1$, Table 2 to those with $\alpha = 2$ and Table 3 to girders shown in Fig. 3. Table 4 again returns to the girder depicted in Fig. 3, but the shape of the curvature is considered exactly as it was measured before testing the girder, but its amplitude varies in several steps. Table 5 returns to the girder seen in Fig. 1, but the web curvature has the shape of the first eigen function of the related linear-buckling theory problem, its amplitude again varying from case to case [3].

In the case of Tables 1 and 2 more than one shape of the initial curvature are considered; they are indicated there as the number of half-waves in the longitudinal direction multiplied by that in the transverse one.

Table 1:

w_0 [mm]	w_0/d	Ultimate load F_{ult} [kN] Shape of initial curvature		
		1x1	1x2	1x3
1	1/1000	731.0	734.8	734.0
4	1/250	719.2	728.0	730.1
5	1/200	714.9	727.5	727.8
10	1/100	687.1	734.0	715.3
15	1/67	655.3	768.7	706.1
20	1/50	622.8	759.8	702.1

Table 2:

w_0 [mm]	w_0/d	Ultimate load F_{ult} [kN] Shape of initial curvature	
		1x1	1x2
5	1/200	564.1	560.3
10	1/100	558.1	548.4
20	1/50	549.5	522.0

Table 3:

w_0 [mm]	w_0/d	Ultimate load F_{ult} [kN] Shape of initial curvature 1x1
1	1/1600	2484.4
4	1/400	2450.6
6.4	1/250	2451.6
8	1/200	2456.8
16	1/100	2453.2
20	1/80	2444.6

Table 4:

w_0 [mm]	w_0/d	Ultimate load F_{ult} [kN] Shape of initial curvature (measured)
1	1/1000	743.2
2	1/500	745.6
4	1/250	744.2
5	1/200	748.2
10	1/100	746.0
15	1/67	737.2
20	1/50	724.6

Table 5:

w_0 [mm]	w_0/d	Ultimate load F_{ult} [kN] Shape of initial curvature (first eigen function)
1	1/1600	2447
4	1/400	2440.2
6	1/266	2443.6
8	1/200	2432
15	1/106	2407.2
20	1/80	2387

An examination of the results obtained reveals the following:

(i) The effect of web initial curvature to a great extent depends on its shape; therefore all practically important (i.e. those that occur in ordinary steel plate girders) configurations need considering and the most unfavourable results need to be taken into account.

(ii) The impact of web initial curvature is not a monotonic function because it is considerably affected (a) by the shell-like behaviour of initially curved webs (which brings about a difference between the monotonic behaviour of an initially curved column and the more complex performance of an initially curved plate, when at least for certain initial curvature shapes and within a certain interval of initial curvature amplitudes, an increase in the amplitude need not always necessarily mean a drop in the load-carrying capacity of the girder) and (b) by snap-throughs which occur during the buckling process of the web.

(iii) In the light of the main objective of the contribution, it is not of primary importance (even though even this can be seen in Tables 1-5) to find out how large is the "absolute" impact of the individual cases of web "dishing", but more important is it to determine what would happen (i.e. how large would be the drop in ultimate strength) if one neglects the usually prescribed tolerances (for the amplitude w_0 of web curvature, usually $w_0 = d/200 - d/250$, d being web depth) and find out the ultimate load for the same girder but with an unstraightened web. For the products of well equipped and fully experienced steel fabricators, it can be expected (see our measurements mentioned hereabove) that for unstraightened webs w_0 is about $d/100$.

From the tables summing up the writers' results, Tables 1-5, it follows that the corresponding ultimate load reduction is very small, less than 4 p.c. It is therefore insignificant for the safety of the girders.

However, given the complex character of the behaviour of initially curved webs, see in particular point (ii) hereabove, further calculations in the aforesaid optics are under way, the writers considering other girder "geometries" and other kinds of web "dishing".

5 CONCLUSION

The conclusions drawn from the authors' study of the effect of (practically important) web initial curvatures on the ultimate load performance of steel plate girders show that it is not indispensable to abide by the currently used and rather stringent web tolerances, and that plate girders can be used without their webs being straightened.

Of course, this conclusion holds only for the products of well equipped and highly accredited steel fabricators, having a staff with high expertise and experience (such as the steel fabricator of Division 7 of METROSTAV, plc., where the measurements described above were carried out), for which it can be expected that the standard of workmanship achieved will be sufficiently high and resulting imperfections reasonably small.

But even then it is advisable to strive to fulfil the four recommendations given by the aforesaid Task Group [5], viz.

(i) Efficient design in balancing welds about neutral axis,

(ii) Avoidance of excessive use of weld metal (this applying to both the number and size of welds),

(iii) Ensure that fit-up is as perfect as can be achieved,

(iv) Use appropriate welding procedures, aware of the fact that automatic and semi-automatic welding yields better results than manual welding.

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