IMPROVING THE FATIGUE RESISTANCE OF STIFFENER/LOWER FLANGE CONNECTION IN STEEL BRIDGE BEAMS.

J. Ménigault*, J. Claeys*, J.M. Vigo** and Y. Le Guernic***.

* SOLLAC, CRDM, BP2508, F-59381 Dunkerque cedex 1, France.
** DH - GTS, BP6317, F-59379 Dunkerque cedex 1, France.
*** Metal Improvement Company Inc., F-45200 Amilly, France.

ABSTRACT

The stiffener/lower flange welded connection is very critical in terms of fatigue resistance, its relative Eurocode 3 fatigue class is low, making more difficult the use of high strength steels in bridge construction. The purpose of this work is to evaluate the level of fatigue life improvement due to shot peening applied after welding. The results are compared to those obtained from the basic welding process without post weld treatment and the basic process followed by GTAW remelting of the weld toe. The fatigue class relative to the basic process without any post weld treatment is above the relevant Eurocode 3 fatigue classes. Shot peening and GTAW dressing generate significant fatigue improvements. If shot peening becomes widespread in the industrial process of bridge beam making, the fatigue class of this critical detail could be revised favouring further development of high strength steel use in bridge construction.

KEYWORDS

Steel, welding, bridge, stiffener, flange, fatigue, shot peening, residual stress.

INTRODUCTION

Construction of steel framed bridges, particularly composite bridges combining steel and concrete, has been growing for the last decade in Europe but is still about three times less than that in USA and Japan (1). In France, the development of the TGV (high speed train) network has needed the construction of numerous composite bridges since 1990. This was made possible through the development of thermo-mechanically processed (TMCP) high strength structural steels with improved weldability and mechanical properties, e.g. 355; 420; 460MPa yield strength steel grades (1). Meanwhile, fatigue has been a growing concern for many years as shown by the well documented papers of Fischer (2)

and Miki and Sakano (3).
Fatigue failures are observed in bridge beams during service time (2,3) as well as on large scale assemblies in laboratory experiments (4-6). Most fatigue failures occur at welded connections, especially at fillet welds (3). Except for the case of orthotropic steel decks which were thoroughly investigated at an European level (6), fatigue failures occur at web/flange, stiffener/flange or stiffener/web connections (2-4,7). The role of web stiffeners is to reduce web deflection (4). In-service fatigue failures in bridges are mainly due to the presence of weld defects, lack of fusion, mishandling during manufacturing, vibrations during transport or service (passage of trains on railway bridges, wind action). Other causes are neglecting fatigue at the design stage and badly estimating fatigue loading spectra (2,3,8).
Most of fatigue cracks initiate early in the life of the structure (3). The preferred initiation site is the weld toe of fillet welds loaded in tension. This is the case for the web stiffener / lower flange connection (3,4,7,9,10). The weld toe is the prime site for fatigue cracking because of severe stress concentration (abrupt change in shape at the toe) and the presence of crack-like imperfections (7-10). Fatigue cracking at the weld root is observed in orthotropic decks under specific conditions (important lack of penetration) [6].
As demonstrated in the above paragraphs, for many welded structures, fatigue is the main design criterion, an allowable loading of the structure has to be defined to avoid fatigue failure. Most fatigue standards relate to specific areas of industry, e.g. bridges, offshore platforms, pressure vessels (9,10). Fatigue design rules were first published by IIW, then included in the ECCS design rules and, finally, incorporated in Eurocode 3 (9-12). These fatigue design rules for welded structures use SN curves based on data obtained from fatigue tests on welded specimens [9]. That permits the establishment of a detail classification system: The fatigue class is the nominal stress range at 95% survival (5% failure) for a fatigue life of 2 million cycles. Each SN curve, therefore each fatigue class, refers to a particular mode of failure for a specified welded construction detail (5,8-12). Sometimes, several fatigue classes are associated with a given construction detail depending on plate or element length, width, thickness, etc... and of manufacturing process (13).

One must notice that this detail classification is not sensitive to the type of steel and weld quality, even if post weld improving techniques are considered. Moreover, the minimum applied stress level, the loading ratio and the type of loading spectrum (constant/variable amplitude) do not play major roles in the classification system. In all cases, tensile residual stresses are assumed to be present at the crack initiation area, so, mean stress effects are neglected. The main factors influencing fatigue resistance are geometry (shape, orientation, etc...) and presence of weld defects, both generate stress concentration at the

site of initiation (5,8-10,13). Crack initiation is neglected. It is true when welding introduces flaws which act like pre-existing cracks (8).
Thus, the fatigue design rules are sometimes regarded as too conservative (4,8-10) and prevent from the use of high strength steels to extend fatigue life if no extra precaution is taken (8).

Post weld improvement techniques really enhance fatigue resistance of welded structures, relevant experimental evidence is extensive. But these techniques are taken into account only in few standards, toe grinding is most acknowledged, due to lack of confidence in improving procedures and subsequent checking (9,10).

Initiation takes 90% of fatigue life for a smooth specimen of base metal while it takes only 10 to 30% of life for welded components without any special or post weld improving method applied. In fillet as-welded assemblies, propagation of microdefects may represent 30 to 90% of fatigue life depending on geometrical parameters (14). Thus, fatigue life of welded components can be increased by increasing the initiation part through a reduction of the weld stress concentration factor, by removing crack-like defects from the weld or removing harmful tensile residual stresses induced by welding (14). Fatigue life improvement is mostly related to an increase of the iniatiation life for all kinds of post weld improvement methods (15,16). Post weld improvement is still efficient under variable amplitude loading conditions (16).

Post weld improvement procedures are then governed by two principles: reducing stress concentration at the weld toe by removing weld defects and/or changing toe geometry, and introducing compressive residual stresses to delay or prevent early crack propagation (true loading ratio and effective applied stress are lower). Toe grinding, GTAW dressing, weld toe erosion by abrasive water jet follow the first principle whereas spot heating, shot/hammer/needle (or wire) peening follow the second principle. Greatest benefit of improvement technique is demonstrated in the high cycle regime which is the standard regime for most welded details.
In industrial applications, the most widely used post weld improvement methods are toe grinding, GTAW remelting (weld profile control), hammer and shot peening (residual stress control) (14).

Shot peening produces surface residual stresses of 70 to 80% of yield stress and subsequent 30 to 100% increase in fatigue performance is currently observed (14). Shot peening increases the proportion of initiation life to 50-80% compared to 25-60% for the as welded condition, as demonstrated by experimental evidence on high strength structural steel welded joints for offshore applications, true fatigue limits are obtained through the shot peening operation (17). Another advantage of shot peening is that the treatment covers large areas (not only weld toes) at low cost [17]. The beneficial effects of shot peening are reduced in the low cycle fatigue regime and in the presence of high compressive overloadings which induces partial residual stress relaxation (17).

GTAW remelting has been tested on all kinds of high strength steel weldments up to 690MPa yield strength (18,19). So, due to the good results obtained and the great amount of relevant papers, GTAW remelting of weld toe can be considered as a reference post weld improving technique.

Weld toe is generally concerned by improvement methods because of ease of access. That means that full potential of weld improvement method is only realized if premature failure from weld root or other locations can be avoided (14). Improvement techniques are usually applied only on the most severely loaded welds due to cost considerations. Moreover improvement techniques are most efficient when the as-welded joints are performed properly.

Use of high strength steels is strongly related to the use of improved welding procedures and/or post weld improving techniques to increase fatigue performance. Fatigue improvement is associated with an increase of base metal yield strength when such techniques are used (14,15,20) whereas no improvement is shown for basic industrial weldments submitted to fatigue action (5,8-10,20).

BACKGROUND OF THE PRESENT STUDY AND TESTING PROGRAMME

The fatigue class according to Eurocode 3 (12) relevant to the connection of a vertical stiffener and the lower flange of a girder is low and is defined regardless of steel grade and welding procedure. This construction detail is critical when designing bridge beams against fatigue (3-5). The purpose of the present work is to evaluate the influence of a shot peening procedure on the fatigue resistance of this construction detail. GTAW (TIG) remelting of the weld toe is also investigated as a reference post weld improving technique (see previous section) in order to make a comparison between shot peening and GTAW remelting procedures (Table 1).
The flange and the stiffener are made of S355N and S355K2G3 steel plates respectively in the annealed condition, provided by the GTS plate mill company. Flange and stiffener respective thicknesses are 25 and 16mm.
Relevant weld macrographs for the basic procedure and basic procedure

followed by GTAW remelting of the weld toe are shown on Fig. 1.

Table 1: Welding and post weld treatment conditions
Common features: welding position 2F (flat) for the three processes and same welding/post weld procedure is applied for the two passes.

PROCESS	#	WELDING AND POST WELD TREATMENT CONDITIONS
Basic procedure (B.P.)	A	Flux-cored arc welding without gas shield Flux-cored wire Lincoln NR232 dia. 1,8mm (AWS A5.20: E 71 T8). Current: 360A DC-. Voltage: 23V. Speed: 30cm/min. Heat input: 17kJ/cm Lack of penetration: 13mm. No post weld treatment.
B.P.+ GTAW dressing	B	B.P. + GTAW remelting of the weld toe. Covered electrodes: Electrode Réfractaire TIG dia. 3,2mm (Tungstène Thorie 2%). Flux: Prodair Argon 12l/min. (N AR B, NFA 81-010). Current: 170A DC-. Voltage: 14V. Speed: 12cm/min. Heat input: 12kJ/cm.
B.P. + shot peening	C	B.P. + shot peening performed by Metal Improvement Company according to standard MIL-S-13165 C (NFL 06 832). Shot type: MI 550 (BA 1400). Almen intensity: 8/10 C (F 20/25 C). Coverage ratio: 150% checked by the Peenscan process.

Residual stress field determination has been carried out on a shot peened specimen. Only residual stresses at weld toe normal to welding direction are measured (measurements done at ENSAM-Paris). These residual stresses are the most damaging ones as they contribute to weld toe fatigue microcrack opening and propagation. The measurements are carried out by means of the X-ray diffraction technique from the plate surface to a depth of 1mm approximately.
In-depth measuements are done by prior electrolytic polishing to remove material layers to the desired depth. Residual stress evolution with depth is shown in Fig. 2. Individual measurements are affected by large scatterbands up to ±75MPa varying from one residual stress value to another. These scatterbands are not reported in Figure 2 in order to keep it easy to read.
Shot peening generates large compressive residual stress fields as expected.

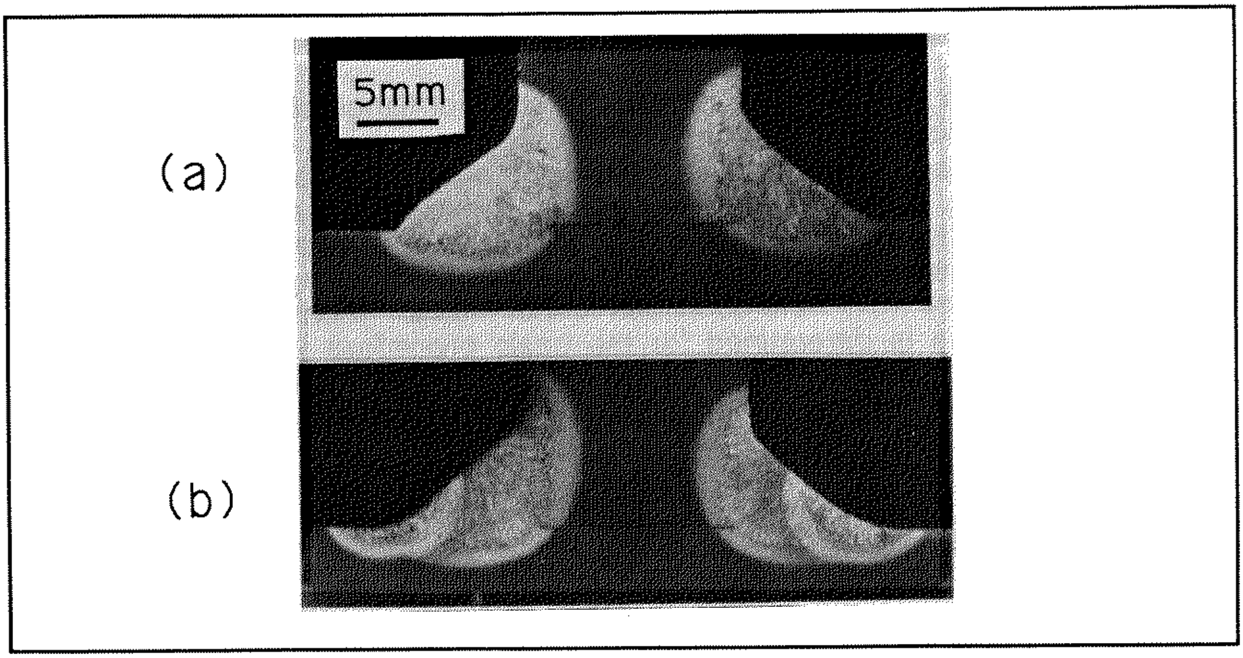

Fig. 1: Weld macrographs. (a) is the basic procedure (A) without post weld treatment while (b) is the basic procedure followed by GTAW remelting of the weld toe (B).

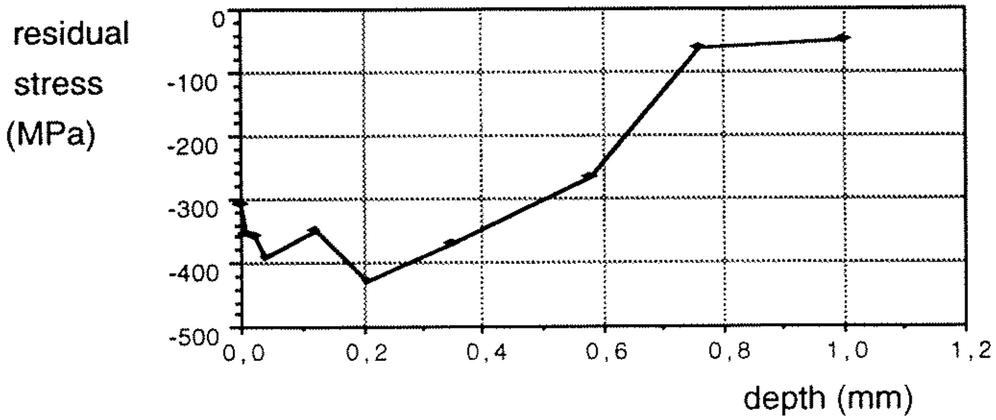

Fig. 2: Residual stress evolution vs depth from the surface (stress components parallel to loading direction) for the basic welding procedure followed by the shot peening operation (C).

FATIGUE TESTING CONDITIONS

Welded Tee joints are used to simulate the stiffener/flange connection. Flange and stiffener thicknesses are 25 and 16mm. The specimens are tested in four-point bending under a stress ratio R of 0,1 using a servo-hydraulic machine. The controlling testing parameter is the nominal stress at the surface loaded in tension at the weld toe according to elasticity theory. Tests are discontinued whether half of the flange thickness is cracked or no cracking is detected at 2 million cycles. Some tests were continued further than 2 million cycles.
A whole SN curve is determined for the basic procedure whereas a limited number of tests at selected stress levels are performed for the two other procedures in order to make a comparison with the basic procedure and between themselves.

RESULTS OF FATIGUE TESTS

General features: All fatigue cracks initiate at weld toe on the flange side 25 tests are carried out for the basic procedure (A). 10 and 9 tests are carried out for the GTAW remelting and shot peening post weld techniques respectively. On the one hand, the SN curve of the basic procedure can be considered as complete (Fig. 3). On the other hand, due to the low number of fatigue tests, the results relative to the two other processes are scattered, associated SN curves are difficult to determine (Fig. 3). The results give only a basis ofr comparison.
Influence of GTAW remelting of the weld toe: This process induces a strong increase of fatigue resistance. This result is consistent with the relevant literature (see Introduction) and previous results obtained on the same kind of stiffener/flange assembly (7). These results show the major importance of geometrical parameters of the weld profile on fatigue resistance as mentioned in (21,22): The weld toe stress concentration factor depends first on the two local geometrical parameters: toe radius and toe angle.
Influence of shot peening: A sharp increase of fatigue resistance is the result of the shot peening procedure, that has to be related to the presence of a large compressive residual stress profile as shown by the X-ray diffraction measurements (Fig. 2). As already mentioned for the GTAW dressing process, this is consistent with the existing literature on the subject (see Introduction). Those results confirms the major role played by residual stresses in the fatigue process of welded components.

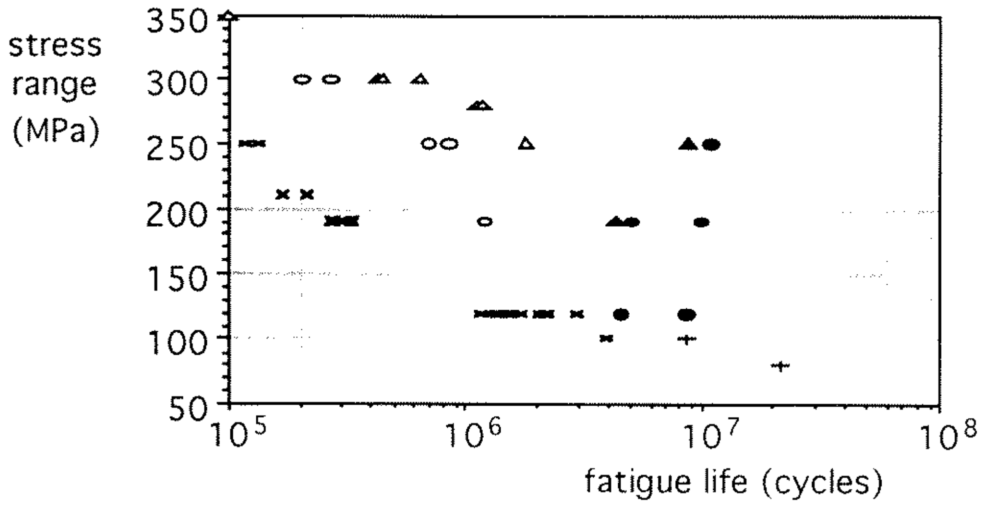

Fig. 3: SN curves relative to the basic procedure (A) and the two post weld improving techniques (B and C). x and +: basic procedure (A). Spots: GTAW dressing (B). Triangles: shot peening (C). x and white symbols: failed specimens. + and black symbols: not failed specimens (run-outs).

COMPARISON WITH EUROCODE 3 DESIGN CURVES

All fatigue data are statistically processed in order to determine fatigue endurance limits for each case and to make comparisons with Eurocode 3 rules. Modelling of SN curves at 50 and 95% survival (5% failure) in the life range investigated is performed. Modelling is done according to the equation

$$\log N = A \log S + B \qquad (1)$$

in which N and S are the number of cycles and the stress range, and A and B are computed parameters. The value of the standard deviation is also given for each case (Figure 4).

97,5% probability of survival and failure values (mean ± two standard deviations) are used to compare processes each other taking into account their respective scatterbands. 95% survival values are used to make comparisons with Eurocode 3 fatigue classes which are 95% survival fatigue limits at 2 million cycles.

Differences in fatigue behavior between processes are clearly shown, highlighting the trends mentioned in the previous section. The scatterband associated with the GTAW dressing procedure is relatively large due to the low number of fatigue tests. More surprisingly, the scatterband associated with shot peening is narrow, even narrower than that of the basic as-welded condition, although the number of tests is almost the same than that of the GTAW dressing procedure. This narrow scatterband can be related to the reliability of the shot peening treatment.

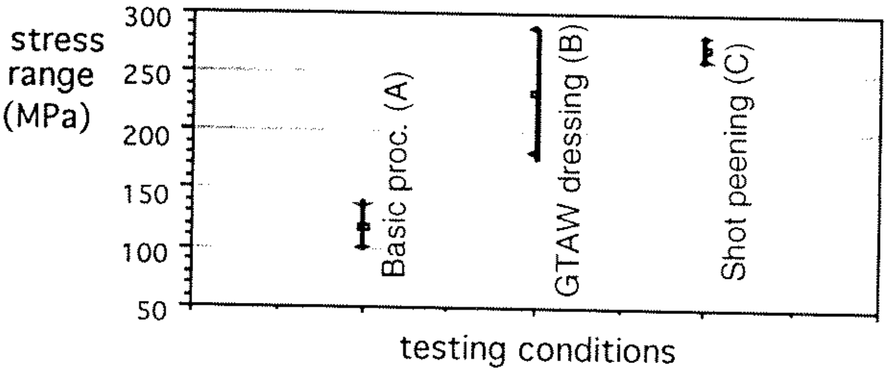

Fig. 4: Comparison of 50% survival mean values of fatigue limits at 2 million cycles and associated scatterbands (± 2 standard deviations) between the basic procedure (A) and the two post weld treatments applied to the basic procedure (B and C).

SN curves at 95% survival according to the model logN=AlogS+B and Eurocode 3 design curves for fatigue classes 71; 80 and 90 are reported in Figure 5. The selected classes are those relevant of the stiffener/lower flange construction detail in Eurocode 3. Class 90 is recommended by the National Application Document (12) while Classes 71 and 80 are those recommended by Eurocode 3 as the stiffener thickness is larger or lower than 12mm.
For the three procedures tested in the present work, the 95% survival fatigue stresses are higher than the three relevant Eurocode 3 design curves (Figure 5). This is particularly true in the high cycle fatigue range.
Nevertheless, one should remember that the above computed fatigue limits and scatterbands are determined from sets of 9 or 10 fatigue tests for each process except the basic procedure (25 fatigue tests). Therefore, this work gives only trends and ideas for further testing that should be performed if firm conclusions have to be given, especially for design purposes.

CONCLUSIONS

Processes providing best fatigue resistance are those which change weld toe geometry and introduce compressive residual stress fields at the weld toe. This is consistent with the fatigue tests which exhibit weld toe fatigue crack initiation systematically. Significant improvements are obtained by GTAW remelting of the weld toe and shot peening.

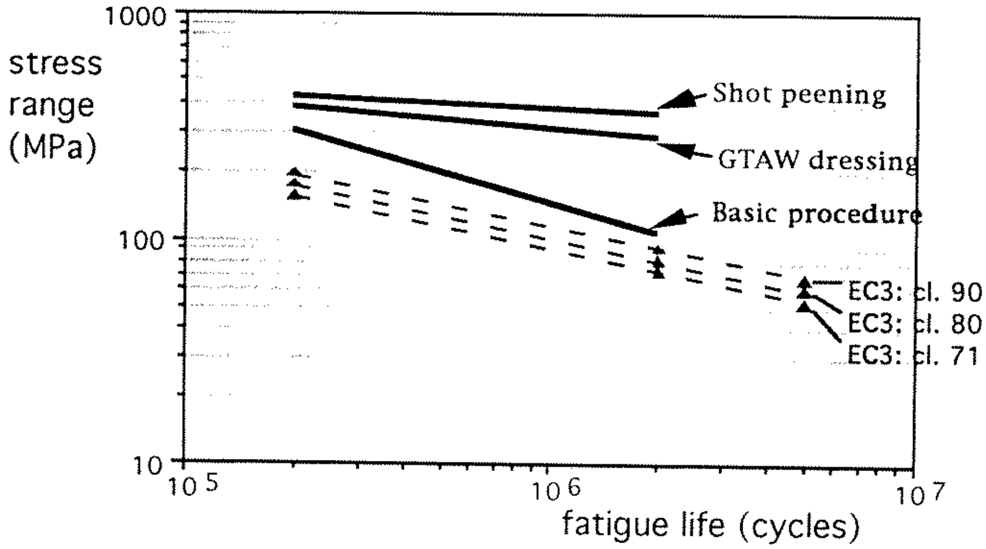

Fig. 5: 95% survival SN curves according to the model: logN=AlogS+B. Dotted lines refer to Eurocode 3 SN curves.

The fatigue limit relative to the basic procedure without any post weld improving technique applied is higher than the three Eurocode 3 fatigue classes relevant to the stiffener/lower flange detail, showing that the fatigue classes are conservative.

Providing relevant fatigue improvement and low scatter (process stability) is confirmed by further testing, the fatigue class of the detail should be much higher if shot peening is envisaged in the bridge beam production process. Shot peening should encourage the development of the use of higher strength structural steels (Y.S. > 355N/mm2) in bridge construction. Shot peening is easier to implement in the industrial process at lower cost than GTAW dressing, toe grinding or hammer peening post weld treatments.

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