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CFRP-Strengthening and Long-Term Performance of Fatigue Critical Welds of a Steel Box Girder

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ABSTRACT: The steel box girder of an artwork pendulum that is mounted at the atrium ceiling of an office building is subjected to alternate bending. After 19 months of service severe fatigue cracks have developed in the welds of the box girder. After evaluation of several repair strategies, the most efficient and cost-effective way of increasing the static and dynamic strength turned out to be the bonding of prestressed CFRP laminates onto the tension and compression flanges of the steel box girder. The performance of this strengthening method was proved by a laboratory fatigue test on a comparable strengthened, smaller sized welded box girder. After 5 Million of alternate bending cycles fatigue cracks were initiated but reached lengths of not more than 20mm. Based on this promising result the steel box girder of the artwork pendulum was dismounted and strengthened by bonding three 6 m CFRP laminates on both girder flanges having an initial prestress of 900 MPa each. Regular inspections of the strengthened box girder have shown, that after 8 years of service since strengthening (3 million load cycles), no visible fatigue cracks were initiated and no prestress loss was monitored.

1 INTRODUCTION

An artwork pendulum in the atrium of an office building was made of a welded steel DD11 (StW22) box girder having a length of approx. 12 m. The pendulum performs an oscillation of ±60° having a period of 24 sec (Figure 1). Assuming approx. 10 hours of service each day, a total of 390'000 oscillations result every year (oscillation frequency: 0.042 Hz).

The steel box girder consists of four sections as indicated in Figure 1. Each section is made up of two web plates and two tension/compression flanges providing a rectangular tube. Longitudinal fillet-welds, located on the outer side of the tube's edges, connect the web plates and tension/compression flanges.

The lower and intermediate sections have a tapered shape in order to minimize dead load. The lower section has a length of 3.665 m. It carries two TV-monitors of 80 kg mass each on its lower end (Figure 1). The intermediate section has a length of 2.985 m. The lower and intermediate sections were connected by circumferential butt welds, denoted as lower joint in Figure 1. The short section next to the intermediate section contains the pivot driving devices. It has a length of 2.09 m. Four T-shaped beams are connected to the pivot drive, two on each side (Figure 2). These four beams are fixed to the atrium’s ceiling, which carries the artwork pendulum. The intermediate section was originally connected to the pivot drive section by a total of 12 HV-screws (Figure 2). The top segment with a length of 3 m contains the balancing weight of the pen-dulum. It was originally connected to the pivot drive section by 12 HV-screws as well (Figure 2).

Figure 1. Artwork pendulum

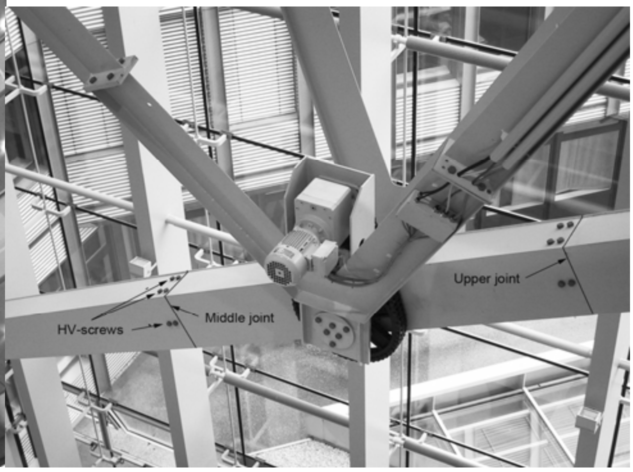


Figure 2. Pivot drive section with originally designed middle and upper joint

After a few months of service in 2000 the head of a screw, connecting the intermediate to the pivot drive section of the steel box girder, broke. As a consequence, the upper and middle joints were butt-welded. However, after another 19 months of service (approx. 620’000 oscillations) significant fatigue cracks developed in the heat-affected zones of the box welds at the lower and middle joint respectively (Figure 3). Moreover, detailed inspections revealed a low manufacturing quality of the welds.

A fatigue strength analysis by Koller (2003) based on the FKM-Guideline (2003) of the welds concluded that the oscillating bending stresses would initiate fatigue cracks (that would grow some time till separation of the cross section) whatever quality the welds are manufactured. Conventional strengthening techniques that add steel plates by adhesive bonding, riveting, bolting, welding or clamping (Hollaway & Cadei (2002)) were no option. Further structural investigations by Koller (2003) showed, that the nominal alternating bending stresses increase due to stress concentrations at notches caused by riveting, bolting or welding. When using steel plates, the dead load of the pendulum would significantly increase since the balancing weight needs an adjustment as well. Several repair options were evaluated with a repair cost minimization, a considerable increase in durability and the visual appearance of the strengthened artwork in mind. It was finally decided to repair the pendulum by local reinforcement of the welds by using high-strength Carbon Fiber Reinforced Polymer (CFRP) laminates, that were adhesively bonded in a prestressed state (Figure 4).

Empa’s research efforts in the 1990’s provided evidence that a considerable increase of the fatigue resistance of welded aluminum beams can be achieved by externally bonding pultruded unidirectional CFRP laminates on their flanges (Meier (2006), Kim et al. (1991), Loher et al. (1996)). In particular, the simple bonding of unstressed CFRP plates using rubber-toughened two-component epoxies over the notoriously fatigue-weak welding zone (butt-welding) of an aluminum beam proved to be an efficient and cost-effective way of increasing the static and dynamic resistance. The reinforcing effect obtained is determined by the stiffness-ratio (the ratio in elastic modulus being $E_{11,CFRP} : E_{Al} \geq 2 : 1$) between ground structure and unidirectional CFRP laminate (Meier, 2006).

One can therefore easily follow that an unstressed CFRP laminate reinforcement of welded beams made of steel will not lead to a substantial increase in durability of the steel structure subjected to fatigue loads. This consideration led to the idea of prestressing an external reinforcement of the welded zone. This technique takes advantage of the local mean-stress effect for increasing the structure's fatigue strength (Bassetti 2001). Hence adhesively applied prestressed laminates will introduce residual compressive stresses into the welds that superimpose the oscillating stresses. Using an appropriate prestress level, the oscillating stresses may be shifted completely into the compressive region. Due to the mean stress influence (FKM 2003) crack initiation will need much more bending cycles and potential cracks would no longer open and grow under service loads.

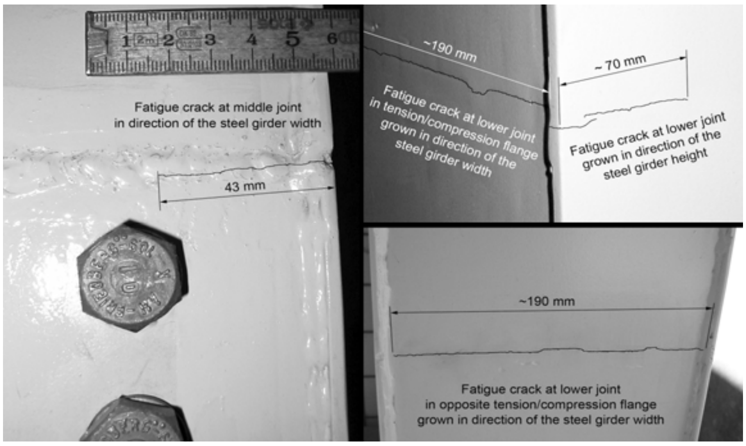


Figure 3. Fatigue cracks in welds after 19 months of service

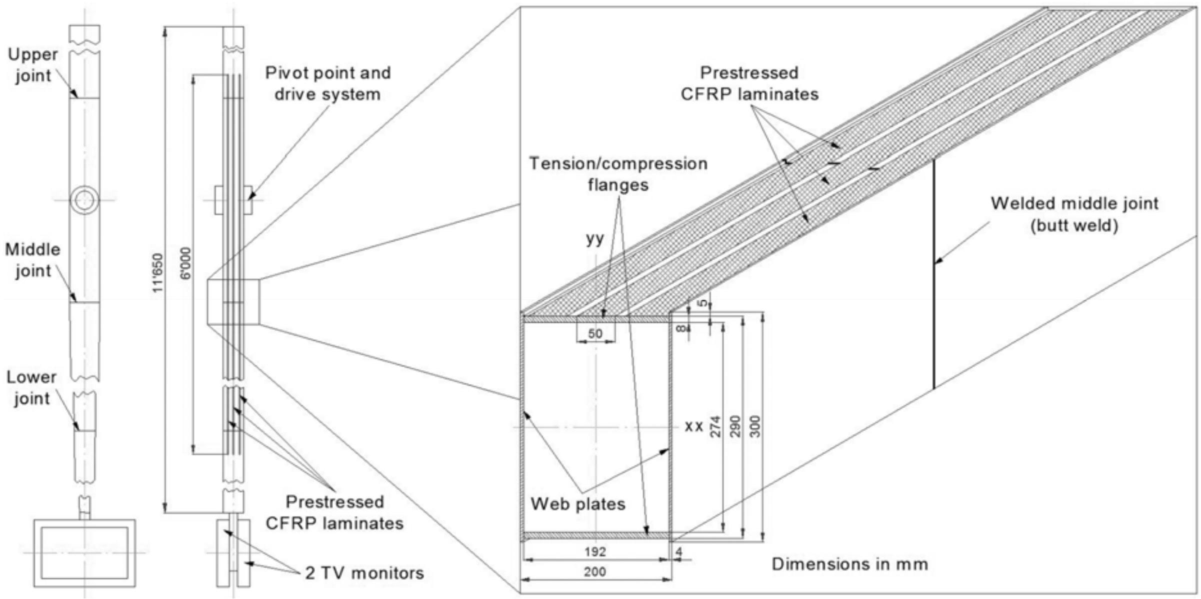


Figure 4. Strengthening principle of welds in the steel box girder; Details at middle joint

2. STRENGTHENING METHOD

2.1 Finite element analysis

Since the pendulum performs an oscillating movement of ±60° in service the bending stresses at the maximum loaded welds at the middle joint (Figure 4) vary from +40.2 MPa to -40.2 MPa representing a stress ratio of R = -1. In order to design a prestressed CFRP reinforcement for a welded steel box girder a finite element model (static, linear-elastic stress analysis) was set up that had three 1 m prestressed CFRP laminates applied on both tension / compression flanges (described in detail in Koller et al. 2012). The finite element analysis showed that a prestress load of 45 kN for a 50 mm x 1 mm thick unidirectional CFRP laminate is sufficient because the residual compressive stress in the critical weld is $\sigma_{res} \leq -45$ MPa, independent of the laminate type. Two commercially available undirectionally reinforced carbon fibre epoxy laminate types were taken into consideration: Carbodur S512 by Sika (2011) with E_{11}=165 GPa and Toray M46J with E_{11}=305 GPa, Toray (2011). Despite of the slightly larger shear stress maximum in the bonding agent at the CFRP laminate ends and the slightly larger adhesive-yield region at laminate ends (Koller et a. 2012), the laminate choice should tend to lower stiffness for not losing too much prestress in cases when relaxation processes in the epoxy adhesive would take place (e.g. at higher service temperatures which approach the T_G being 80°C of the adhesive Scotch Weld® 9323 B/A used). Furthermore the strength capacity of thinner laminates is used more efficiently at a lower price. Hence the thinnest laminate available having a thickness of t = 1.0 mm was chosen for strengthening the steel box girder.

2.2 Experimental verification

An experimental verification of the strength behavior under fatigue loading was mandatory, since limited experience exists for strengthening steel structures using adhesively bonded prestressed CFRP laminates (see e.g. Bassetti 2001). As it was too expensive to test the real steel box girder, the same company that had delivered the pendulum manufactured a smaller sized specimen (2:5 in scale) containing a circumferential (butt) weld. Material and welding process were identical to the original steel box girder (Koller et al. 2012).

The laboratory experiment showed that the downscaled and CFRP reinforced girder specimen withstood 5 million bending load cycles (oscillation movements at 3.5 Hz) at the same stress amplitude at the weld as the pendulum girder (R = -1) without failure (Koller et al. 2012). 5 million oscillation movements of the artwork pendulum represent a life time period of approx. 13 years. This finding, the experimental assessment of the absence of prestress losses over 5 million load cycles and a remaining load carrying capacity of over 150% of the maximum service moment after additional 2.22 million load cycles (Koller et al. 2012) were decisive for the implementation of the presented strengthening method on the full-scale artwork pendulum.

3. STRENGHTENING AND MONITORING THE ARTWORK PENDULUM

After demounting, the pendulum was delivered to Carbo-Link GmbH, which carried out the strengthening of the steel box girder. The locations of the three butt welds in the pendulum are shown in Figure 6. Visual inspections revealed transverse cracks having considerable length (up to 190 mm) in all three butt welds (Figure 3). A fatigue life of approx. one year of service was calculated based on the FKM-Guideline (2003). The cracks found in the butt welds as well as the reported service period of 19 months confirmed this prediction for the fatigue life.

The CFRP strengthening of the steel box girder performed by Carbo-Link GmbH included the following steps:

1. Grinding of all transverse butt welds of upper, middle and lower joint.

2. Renewing of the butt welds of all joints along the circumference by inert MAG welding using a S235 welding rod (D = 5mm).

3. Removal of all screws at the upper and middle joints.

4. Removal of the coating on each flange in the range from the upper to the lower joint.

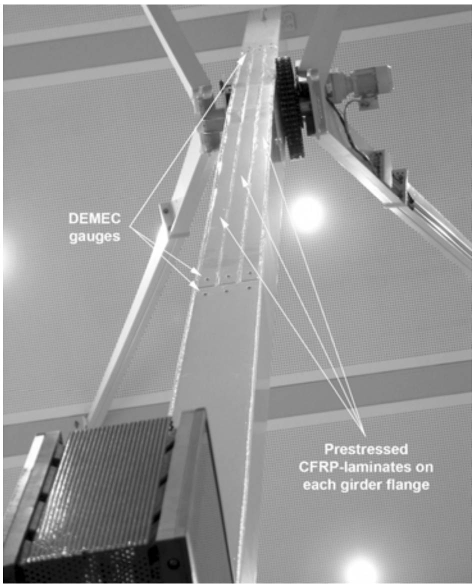
5. Application of three prestressed CFRP laminates (Carbodur S512 grinded on both sides, F_{pt} = 45 kN, w = 50 mm, t = 1 mm, E_{11} = 165'000 MPa) on each girder flange following the application procedure described in Meier et al. 2001. A glass fiber fabric (by R&G GmbH, thickness = 0.22 mm, specific weight = 225 g/m^2) was put between steel girder and CFRP laminates in order to have an electrically insulating layer as well as to define the adhesive layer's thickness. Scotch-Weld epoxy adhesive 9323 B/A was used to bond the prestressed CFRP laminates onto the steel box girder. The application of the prestressed CFRP laminates followed the same procedure used for strengthening the laboratory girder specimen.

6. Application of a new color coating.

7. Transporting the reinforced pendulum to the owner.

8. Mounting of the artwork pendulum.

9. Recommissioning of the artwork pendulum on June 14th, 2004 (Figure 5).



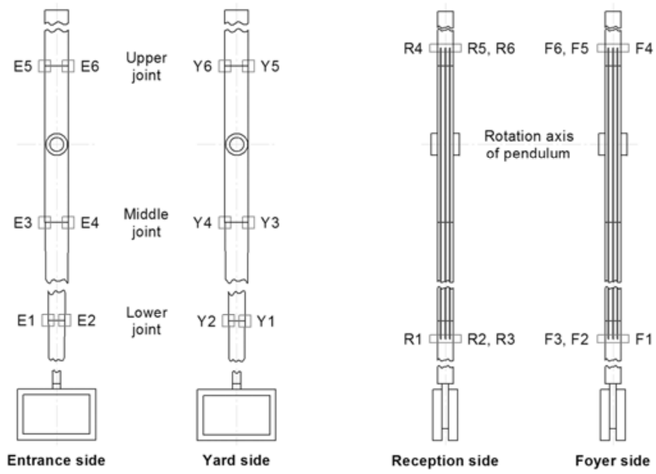


Figure 5. Six prestressed CFRP laminates bonded on the flanges of the artwork pendulum

Figure 6. Location and denomination of butt welds and prestress measuring points at CFRP lam. ends

In order to monitor the behavior of the strengthened artwork pendulum (Figure 5), periodical inspections were agreed to take place. Besides all the bolt connections, the circumferential butt welds and the condition of the CFRP laminates are inspected periodically every year. In this period the pendulum performs approx. 390'000 oscillation movements. The inspections take place on-site at the not dismantled, vertically oriented steel box girder. A moving working platform is needed to reach all inspection points.

The butt welds (Figure 6) are inspected visually using a binocular eyepiece having a magnification factor of 10. The minimum detectable crack length using this method is ±0.1 mm. With an electric LED-torch the heat affected zones of the welds are illuminated. Special attention is given to the locations of the three girder joints. In each case the four edges were carefully inspected. After 8 years of service no cracks were detected.

The inspection of the CFRP laminate bonding is performed by smoothly knocking on the laminate surface using a coin. An intact bond will respond by a clear sound, a damaged one by a dull sound. No delamination could be detected by this tapping test after eight years of service.

Measuring the displacements between two DEMEC gauges, each 100 mm apart from the laminate end, was used to monitor the prestress state of the CFRP laminates. One point is mounted on the laminate, the other one on the flange of the steel box girder (Figures 5 and 6). In case of a prestress loss (creep of the adhesive layer) the laminates would contract and hence the distance of the DEMEC gauges would increase. These distances are measured by using a precise displacement-measuring device (type ‘Deformeter’: Accuracy: ±0.001 mm, basis length: 200 mm). Spacing measurements carried out in August 2004 are considered as reference values. For all subsequent measurements the changes are evaluated that give an indication on the variation of the prestress.

Figure 7 shows the changes in measuring point spacing for all twelve monitored laminate ends (six on each girder flange) as a function of the number of performed oscillations. As can be noticed from Figure 7 the distance changes are varying in positive and negative direction around the origin, which represents the reference measurement. Especially negative changes would stand for increasing prestress. However, increasing prestress may result only from temperature-based expansion of the steel box girder (coefficient of thermal expansion CTE for CFRP in fiber direction: $\alpha_{CFRP} = 0\ K^{-1}$, steel: $\alpha_{St} = 12 \cdot 10^{-6}\ K^{-1}$). Positive as well as negative changes are of the same magnitude. Since the artwork pendulum is mounted in an entrance hall with a glass facade, temperatures may vary from 32°C in summer to 16°C in wintertime. Hence temperature variations of ±8°C cause thermal expansions of the steel girder of ±0.02 mm between DEMEC gauges.

Furthermore it has to be mentioned that measurements using a Deformeter take place under hindered conditions. Since a moderate contact pressure is needed to perform the measurements, the pendulum may draw aside and measurement errors in a range of ±0.02 mm were assessed on site. Hence, all measurement results denote that the prestress level variation remains in the range of normal temperature variation and measurement uncertainties, respectively. From the measurement results scattering around the reference value (Figure 7) one concludes, that no loss of prestress occurred in the six CFRP laminates within the past operation time of eight years.

4. DISCUSSION AND CONCLUSIONS

The welded steel box girder of the artwork pendulum was dismantled, all welds renewed and the two tension/compression flanges strengthened by three prestressed CFRP laminates in the vicinity of the maximum bending moment. The laminates having a length of 6 m and a cross section of 50 x 1 mm have been prestressed at 900 MPa (45 kN each laminate). Hence the resulting nominal stresses in service (bending superposed to compressive stresses) remain throughout in the compressive region. After repainting the pendulum, the strengthening is hardly visible to the naked eye, which was an obvious criterion for the artwork. After more than eight years of service and 3 million oscillations, regular inspections of the strengthened pendulum have revealed neither indication of prestress loss nor delamination, and no initiated fatigue cracks were found.

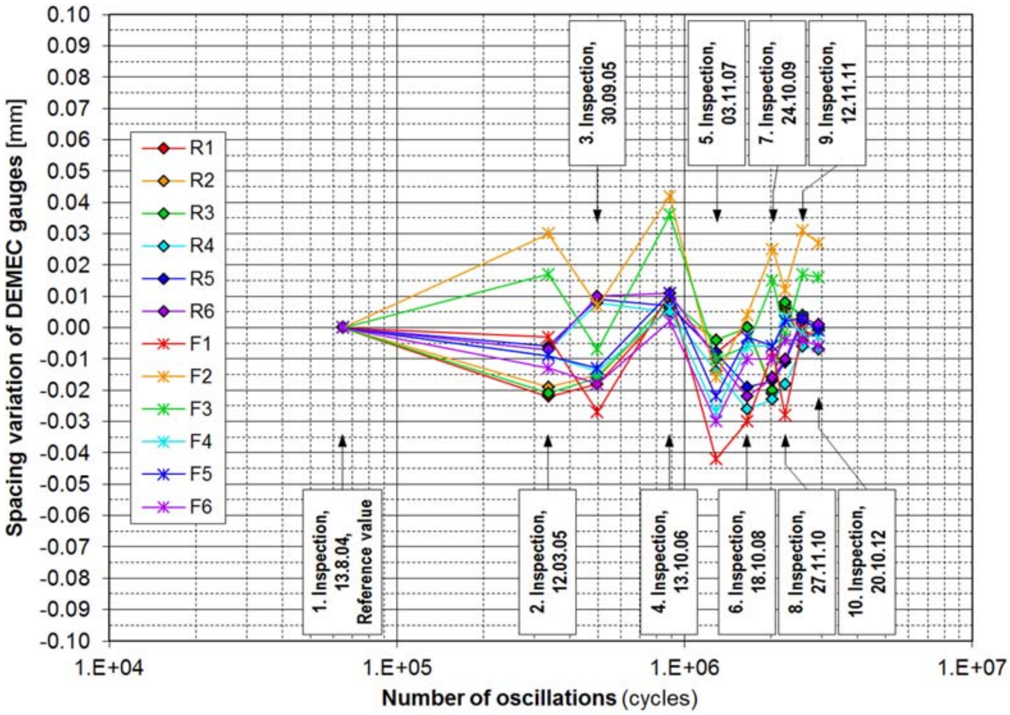


Figure 7. Spacing variation of DEMEC gauge as a function of the number of oscillations

To date, the reached number of oscillations represents an increase in fatigue lifetime by a factor of almost five compared to the welded, not reinforced pendulum girder. This factor is expected to increase in the future. For a scaled girder specimen a factor of eight was obtained from a laboratory fatigue test (Koller et al. 2012). Hence the strengthening method appears very promising in order to reach the aimed fatigue lifetime of at least ten years without development of significant crack length.

However, the successful strengthening of this steel member bases on favorable boundary conditions:

• The long-term behavior of adhesively bonded joints is influenced by humidity and/or liquid water resulting in a time-dependent deterioration (Shaat et al. 2004). Cohesive or adhesive-type failures may result. The artwork pendulum is mounted in an entrance hall. Compared to outdoor service, limited temperature variations (15°C ≤ T ≤ 35°C) as well as moisture variations (30% ≤ rH ≤ 60) occur during service of the pendulum. Large variations of environmental conditions may cause increased aging of the bonding layer over time and therefore may have negative influences on the strengthening (debonding and/or prestress loss) which were not observed in the present application. Beside the more or less stable environmental conditions of the entrance hall, the applied color coating after strengthening acts as a supplementary protection.

• Several investigations reported on the presence of peel-off stresses normal to the adherend at the laminate ends (e.g. Hollaway and Cadei 2002 or Shaat et al. 2004). Some author proposed the need of clamping systems to reduce out-of-plane “peel-off” stresses when applying prestressed CFRP laminates to steel members. Peel-off stresses turned out as not critical after application of the CFRP laminate on the pendulum girder, since prestressing was only about 32% of the ultimate strength of the laminate. The pendulum girder did not show any indications of delamination at the laminate ends after eight years of service. It is considered important, that the ends of the applied CFRP laminates with a length of 6 m each are located at low fatigue stressed regions, near the ends of the steel box girder. Since the bending moment vanishes at the pendulum ends, the fatigue load transfer from the steel flanges into the CFRP laminates is also low. Hence the shear stress maxima in the bonding layer at the laminates' ends have an almost static character, which is very beneficial with respect to the strength of the bonding layer. In an additional Empa investigation by Ebnöter (2007) it was observed that oscillating shear stress maxima lead to early debonding of applied prestressed CFRP laminates.

• As already mentioned, welds are supposed to contain welding defects, which act as stress concentrators and fatigue crack starters respectively. Welds also contain residual stresses in the heat-affected zones that may reach the height of the yield stress of the steel material. These residual stresses were not taken into account, when determining the needed prestress force of the CFRP laminates. A higher prestress than 32% of the laminate's ultimate strength would have been needed to shift the maximum tension stress (superposition of tensile fatigue stresses and residual stresses) into the compression region.

Since residual tension stresses remain in the weld after strengthening, it appears evident that superposed alternate loading may initiate fatigue cracks even in case the nominal stresses are shifted completely to the compression region. However, fatigue cracks developing in the heat-affected zone of the weld will reduce these residual tensile stresses. As a result compressive nominal stresses will then promote crack closure effects and hence slow down crack propagation (Shaat et al. 2004).

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