KNOWLEDGE SHARING

⇒ WELDFAB 2019
⇒ EVENING COURSE ON “WELDING TECHNOLOGY FOR FRESH ENGINEERS” BY IWS, SZ
⇒ LECTURE PROGRAMME BY COIMBATORE CENTRE

TECHNICAL PAPERS

⇒ POST FIRE TENSILE PROPERTIES OF S355 J2 STRUCTURAL STEEL WELDED CONNECTIONS
⇒ EVALUATION OF STRUCTURAL INTEGRITY OF REPAIRED DYNAMICALLY LOADED ENGINEERING COMPONENT

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INTERNATIONAL CONFERENCE & EXHIBITION ON “WELDING & FABRICATION TECHNOLOGY” – WeldFab 2019 AT NEW DELHI

Between 25 and 26 April 2019, a two day International Conference & Exhibition on “Steel, Industrial Materials & Non-Metallic’s (Materials’19)” and “Welding & Fabrication Technology (WeldFab’19)” was conducted by Matcorr in association with IWS as knowledge partner. The two day event was unfolded at Hotel Crowne Plaza, Mayur Vihar, New Delhi.

Steel, Advanced materials and the developments, Advances in Welding, Fabrication & Cutting Techniques, Metallurgy of Welding, Characterization, Inspection & NDE of Welding, Challenges in Welding of Stainless Steel & High Alloys, Welding of Line Pipe Material, Welding of Pressure Vessels, Tanks, Boilers, Mechanical Behavior & Weld Integrity, Automatic & Robotic welding, Shipbuilding, Underwater Welding and Welder Training & Certification are the areas that have been discussed in the deliberations of the two days in the well attended programme.

Dr. Ashok K Srivastava, Director, Center for Steel Technology and Product Development, Professor and Head, Department of Metallurgical and Materials Engineering, OP Jindal University, JSPL, Mr. K K Pahuja, President, ISSDA, Mr. Ashish Agrawal, Director, Jindal Stainless Steel and Dr. Mukesh Kumar, Director, SRTMI, Ministry of Steel, Govt. of India illuminated the inauguration of the event with their gracious presence. Mr. M P Jain, Vice President, IS graced the occasion and chaired a technical session.

Experts from various organisations including ISRO, DRDO, Kemppi India, L&T, Wearresist, Jinal SS, Welspun, IIT Pune, Techcellent Inspectorate, Olympus, SSPC shared their research works and experience with the delegates.
EVENING COURSE ON “WELDING TECHNOLOGY FOR FRESH ENGINEERS” BY IWS, SZ

Between 20th May 2019 and 26th May 2019, IWS, SZ has conducted its flagship course, the evening course on “Welding Technology for Fresh Engineers” at the Institution building premises. The course contains 16 sessions of class room lectures and two sessions of visit to WRI workshop and labs, to get a firsthand knowledge of the latest trends in welding technology. The lectures were delivered by experts from BHEL and WRI and the visit lazed with demonstrations.

The sessions deliberated on the following topics.

- Introduction to Welding Processes
- Shielded Metal Arc Welding
- Submerged Arc Welding
- Gas Metal Arc Welding
- Gas Tungsten Arc Welding
- Basic Metallurgy & Heat Treatment
- Welding of Carbon Steels
- Welding of Alloy Steels and Stainless Steels
- Welding Symbols
- Mechanical Testing
- Welding Processes for Automotive Sectors
- Residual Stress & Distortion in Weldments
- Weld Defects, Causes and Remedies
- Liquid Penetrant Inspection and Radiography Inspection
- Magnetic Particle Inspection and Ultrasonic Inspection
- Welding Procedures and Welder Qualification as per ASME & AWSD.1

LECTURE PROGRAMME BY COIMBATORE CENTRE

The Coimbatore Centre of IWS organised a free lecture programme on the evening of 20th June 2019, at PSGCT, Coimbatore. Dr. K Asokkumar, former Secretary of IWS and the speaker of the day delivered the lecture on “Recent Trends in Welding for Automobile Industries”. The programme was attended by members of Coimbatore Centre. The programme was organised in association with Centre of Excellence in Welding Engineering and Technology, PSGCT, Indian Institute of Metals, Coimbatore Chapter and ISNT Coimbatore.
POST FIRE TENSILE PROPERTIES OF S355 J2 STRUCTURAL STEEL WELDED CONNECTIONS


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ABSTRACT

Structure stability and survival after exposure in fire is very detrimental and critical not only in the region of unwelded parent metal (PM), but also in welded connections too. All the structures build by involvement of lot of welding process like shielded metal arc welding (SMAW), gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), flux cored arc welding (FCAW) and submerged arc welding (SAW). The published information on elevated temperatures or residual material properties of various steels has exhaustive focus on the mechanical properties of PM only. This paper presents the comparative results of S355 J2 structural steel joints made by GMAW and FCAW after exposure to fire up to 900 °C.

Key Words: Structural steel, Post fire properties, GMAW, FCAW, Microstructure

1.0 INTRODUCTION

Due to its superior strength-to-weight ratio, S355 steel is becoming still increasingly attractive in many structural and architectural applications [1] like main beams, stiffeners and cross bracing [2] universal beams, channels and angles [3] smaller diameter penstocks in small-scale hydroelectric plants, the penstock lines and bifurcations, windmill Tower [4]. Steel structure stability and survival after exposure in fire is very detrimental and critical not only in the region of unwelded parent metal, but also in welded connections too. It is therefore really necessary to correctly evaluate the performance of welded connections under fire conditions. The comparison results of cold-formed high strength steel at elevated temperatures with design values in the European, American, Australian and British standards revealed the necessity of proposing specified design rules for material properties at elevated temperature [5]. Thermal and mechanical properties of Q345 steel pipe at elevated temperatures revealed that the yield strength and elastic modulus of Q345 steel pipe decrease gradually with increasing temperature [6-7]. High strain rate behaviour of S355 structural steel in tension at elevated temperatures was studied and reported at 550 °C, an increase of strength and a decrease of ductility was observed due to blue brittleness. Also, a noticeable increase in the effective strain rate was observed at elevated temperatures [8]. Butt welded connections showed more reduction in tensile strength than the parent metal (PM) after exposure to elevated temperatures and also showed more strength reduction in natural cooled samples than water cooled samples [9]. A new design
method was proposed from the post-fire residual behaviour of welded hollow spherical joints of Q235 and Q345 steels at 600 °C, 800 °C, and 1000 °C [10].

Liu et al [11] evaluated the post-fire residual mechanical properties of Q235 and Q345 steel butt welded joints, results revealed that post-fire properties of welded joints were affected with respect to materials grade and heating temperature. The published information on elevated temperatures material properties of various steels has exhaustive focus on the mechanical properties of PM. Very few works studied and reported on welded connections fabricated with various structural steels Q235, Q345, Q420, S355, S450, S690, S960, S1200 have only concentrated on room temperature designs and very little or no information exists for the elevated temperature design of welded connections. However, there is a lack of research on effect of welding process on joints tensile and metallurgical characteristics at elevated temperature. So, it is necessary to explore insight information about the tensile and microstructural behaviour of welded of S355S J2 structural steel connections at high temperatures. This paper presents comparative results of S355 J2 structural steel PM, GMAW and FCAW joints during and after exposed to fire temperatures up to 900 °C.

2.0 EXPERIMENTAL

The experimental programme was designed in accordance with the requirements of BS EN ISO 15614-1:2004+A1:2008 (BS EN ISO 2008) [12], BS EN ISO 6892, Part 1 (BS EN ISO 2009) [13] and BS EN ISO 6892, Part 2 [14]. 8 mm thick S355 J2 high strength hot rolled steel plates were used in this investigation. Plates of dimension 150 mm x 750 mm x 8 mm were shear cut from a large as-received rolled plate. The chemical composition and mechanical properties of S355 J2 PM and filler wires used in this investigation is presented in Table 1 and Table 2 respectively. For fabrication of welded connections, traditionally used GMAW and FCAW process were selected in this investigation for its productivity and ease of suitability with other structural steels in addition to the considered S355 J2 plates. The parameters used to fabricate the joints are presented in Table 3. Necessary care was taken to avoid joint distortion and to get defect free welds. Multi-pass welding procedures with stringer bead technique was used to deposit. Figure 1 reveals the joint configuration and tensile specimen dimensions. For metallography analysis, the weld cross sectional specimen of size 50 mm X 8 mm X 10 mm were extracted. After fabrication of joints specimen for tensile properties were carefully extracted by eliminating 50 mm from both ends of each joint to avoid probable starting and end side defects of the welded joints. For evaluating residual properties, specimen is heated to a target temperature at a rate of heating of 5 °C / min and soaking for 20 minutes. After reaching the target temperature and allow the specimen to cool down to room temperature by natural cooling. Then the tests were performed to evaluate tensile behaviour, hardness behaviour and microstructural examination. Figure 2 represents the photograph of tensile tested specimens.

For ambient temperature and post fire residual properties evaluation, the facilities in CEMMPRE - Centre for Mechanical Engineering, Materials and Processes, Department of Mechanical Engineering was used. The residual factor is calculated as the ratio between respective strength
at post fire temperature with respective strength at ambient temperature. The optical microstructure of the joint was analysed at various locations using optical microscope. The specimens were etched using 2% Nital for PM and HAZ region. The analysis of microstructures was done using an optical microscope Leica DM 4000 M with various locations and varying magnifications. Vickers’s micro hardness testing machine (Make: Shimadzu, Japan; Model HMV-T1) was employed with 0.2 kg load for measuring hardness on across the weld as per ASTM E-384-17 guidelines (ASTM, 2017) [15]. The micro hardness profile was drawn using a measured hardness values across the weld centre line (WCL) of the fabricated joints. More than 25 readings were taken at an interval of 0.5 mm in each zone and values are used for plotting micro hardness profile of each joint, each temperature post fire conditions used in this investigation.

3.0 RESULTS AND DISCUSSIONS

3.1 Ambient and Residual Tensile Behaviour

Figure 3 shows the residual tensile behaviour of the two samples of PM (Figure 3 (a)), GMAW joint (Figure 3 (b)) and FCAW joint (Figure 3 (c)). From these figures, it was understood that both samples follow similar trends. But, when post fire temperature increases from ambient temperature, YS and UTS degrades successively irrespective of the conditions (PM, GMAW and FCAW). One significant observation from these curves are at 300°C post fire condition, there was a small increment in YS and UTS was observed. When post fire temperature increases from ambient temperature to the elevated temperature, YS and UTS both deteriorated sequentially irrespective of the conditions (PM, GMAW and FCAW). Table 4 shows the residual tensile properties of PM. From this table it is understood that, at 300°C, there is a small increment in yield strength and then post fire temperature increases, YS and UTS decreases. From this table, the residual factor also calculated as the ratio between respective strength at post fire temperature with respective strength at ambient temperature. This will give an idea about the reduction factor for this PM in post fire safe service conditions. At 900°C post fire, the residual factor is very minimum is an indication of maximum reduction in strength of this PM. Table 5 shows the post fire residual tensile properties of GMAW joint. From this table, it is understood that, at 300°C, there is a small increment in yield strength of sample 2, while sample 1 shows a small decrement. The reason for decrement in yield strength and reduction factor might be the fracture at bolt hole. From this table 4, it is also observed that all the specimen fractured at PM location is a good indication of strong weld and is capable to withstand its joint integrity up to 600°C post fire condition. But, at 900°C post fire condition, the failure location is at the weld joint interface between fusion line and HAZ. The reason for this will be discussed with microstructure correlation later in this article. But, as similar to the PM, when post fire temperature increases, YS and UTS decreases sequentially. As compared to the reduction factors of PM, the reduction factors of GMAW joints are less. So, it was understood that the welded connections made by using GMAW for structural welding of this S355 J2 steel are satisfactory even in post fire conditions too.
Table 6 shows the residual tensile properties of FCAW joint. From this table it is understood that, at 300° C, there is a small increment in YS and UTS of both samples. But, as similar to the PM and GMAW joint, when post fire temperature increases, YS and UTS decreases sequentially. From this table, the residual factor indicated that maximum reduction in strength values at 900° C the minimum reduction is at 300° C post fire condition. As compared to the reduction factors of PM and GMAW joints, the reduction factors of FCAW joints are high. Less. From this table it is very clear that at 600° C post fire condition, an average of 2 % reduction in UTS in GMAW joints, but in FCAW joint showed that 16 % reduction in UTS. This is a remarkable reduction in UTS after post fire conditions service of the welded connections made by using FCAW process for welding of this S355 J2 structural steel plates. Definitely it would be still worse after 900° C post fire conditions of this FCAW joints. From this post fire tensile test results the residual tensile properties indicated from the Table 4, Table 5 and Table 6 it was understood that, when fire temperature increases, the reduction in tensile properties were more. In these welded connections of S 355 J2 structural steel made by using FCAW process deteriorates higher tensile properties than welded connections made by using GMAW process at post fire service conditions. The reason for this more reduction in FCAW joints will be discussed further in this article by correlating micro hardness and microstructures.

3.2 Ambient and Residual Hardness Profile

For the comparative analysis, hardness profile at the top of the weld region was taken in to consideration for all the different post fire conditions because of the wider region at the top and is close to the surface which would be severely affected by any fire. Figure 4 represents the comparative hardness profile of the joints fired at different temperature. The residual hardness profiles as compared to the as welded joints hardness profile represented as 25° C, reveals that there is a continuous reduction with respect to the increase in post fire temperature. The profile is nearly same up to the temperature 600° C except the decrease in hardness level with respect to the increase in heat treatment temperature. But, when the post fire temperature is increased to 900° C, the profile is also altered in addition to the huge reduction in hardness. The hardness profile of sample fired to 900° C, shows nearly flat profile irrespective to the location of the weld joint (weld centre, interface, HAZ and PM).

3.3 As welded and Post Fire Microstructures

The mechanical behaviour of PM and GMAW and FCAW joints after being cooled from fire temperatures to room temperature is strongly dependent on the effect of the elevated temperature exposure on its microstructure. In order to justify the microstructural changes occurring in the PM, GMAW and FCAW joints specimen after cooling phase of fire, micrographs were obtained from the PM, as welded GMAW and FCAW joints in its different post fire conditions and compared with as welded ambient temperature microstructure. Figure 5 displays the PM microstructure at different post fire conditions including as received PM (Figure 5 (a)). Compared to the as received microstructure (Figure 5 (a)) the microstructure after fire to elevated temperatures shows the continuous grain coarsening from 300° C (Figure 5 (b)), 600° C (Figure 5
Also carbide segregation at the grain boundaries is very clearly visible in the fired samples. Up to 300° C fire, the grain coarsening effect is very minimum, but, carbide segregation is visible at the grain boundaries (Figure 5 (b)). While in specimen fired to 600° C, the microstructure (Figure 5 (c)) shows both grain coarsening effect and also the carbide segregation. Whereas specimen fired to 900° C, the microstructure shows highest grain growth and carbide segregation (Figure 5 (d)).

Figure 6 shows the Fusion Zone (FZ) microstructure of GMAW joint as welded (Figure 6 (a)), post fired to 300° C (Figure 6 (b)), 600° C (Figure 6 (c)), 900° C (Figure 6 (d)). The microstructure of GMAW weld metal fusion zone (FZ) in as welded condition consists of various morphologies of ferrites like WF (marked as A in the microstructure), bainite (marked as B in the microstructure), PF (marked as C in the microstructure) and GBF (marked as D in the microstructure) (Figure 5 (a)). The weld metal microstructure fired to 300° C shows that there is a gradual increment in the size of the grain boundary ferrite and more carbide segregation (Figure 6 (b)). While in Fig 6 (c) the weld metal microstructure fired to 600° C, reveals more grain coarsening at the GBF and carbide segregation is clearly visible. In the weld metal microstructure fired to 900° C, shows highest grain coarsening and the reduction of carbide segregation as compared to the sample fired up to 600° C. The major difference in this microstructure is the presence of various morphologies of ferrite structure in other samples is completely changed to regular equiaxial ferrite pearlite structure (Figure 6 (d) by the application of fire and cooling.

Fusion zone (FZ) microstructure of FCAW joint in as welded (Figure 7 (a)), fired to 300° C (Figure 7 (b)), 600° C (Figure 7 (c)), 900° C (Figure 7 (d)). The microstructure of FCAW FZ in as welded condition consists of various morphologies of ferrites like WF (marked as A in the microstructure), bainite (marked as B in the microstructure), PF (marked as C in the microstructure) and GBF (marked as D in the microstructure) (Figure 7 (a)). In this microstructure, the prior austenite grain boundaries are clearly visible and are coarser as compared with FZ microstructure of GMAW joint. The FZ microstructure fired to 300° C shows that there is a gradual increment in the size of the grain boundary ferrite and more carbide segregation (Figure 7 (b)). While in Figure 7 (c) the FZ microstructure fired to 600° C, reveals more grain coarsening in the grain boundary ferrite and carbide segregation is clearly visible. The FZ microstructure fired to 900° C, shows highest grain coarsening and the reduction of carbide segregation as compared to the sample fired up to 600° C. The major difference in this microstructure is the presence of various morphologies of ferrite structure in other samples is completely changed to annealed equiaxial ferrite pearlite structure (Figure 7 (d) by the application fire.

In post fire tensile test results of PM, GMAW joints and FCAW joints, it was observed that at 300° C, there was a small increment in YS and UTS. After 300° C, there was a continuous reduction in YS and UTS. The maximum reduction in strength properties observed was at 900° C post fire condition. All these observations can be correlated to the microstructure developed due to the post fire condition and hardness properties after fire. Here, in this investigation, after fire, standard air (natural) cooling method was studied since, up 800° C post fire condition, there has not been much significant deference was observed between water cooling or air cooling [16]. It
was understood that by implementing natural cooling the rate of cooling would be 1° C/sec or 60° C/min [17]. But, around 300° C, observed increment in tensile properties shall be justified as follows: During mechanical tests or deformation of steel at temperatures in the range of 200° C – 300° C, the blue oxide film is formed on the surface of these low carbon steel plates. This will lead to strength increases and the plasticity and ductility decrease [18]. This is because the change in the slip movement i.e. plastic deformation results from jump like movements, so the resultant strength properties increment was observed at 300° C post fire samples. Not only the blue brittleness, but also dynamic strain aging during deformation at elevated temperature especially, by 200-300° C is the reason for the increase in YS and UTS of steels [19]. Similar kind of strength increment in post fire conditions were reported [20-22]. After 300° C, the reduction factors decrease because of the continuous loss of YS and UTS as compared to ambient temperature (25° C) and (or) 300° C post fire conditions. With reference to Figure 4, the comparative hardness profile also in line with the strength reduction factor between 25° C and 300° C post fire conditions. Because, from the comparative hardness profile, it is understood that no major hardness reduction is visible from the ambient temperature hardness and 300° C post fire hardness profiles. This gives a confidence that due to fire condition up to 300° C, not much hardness change could also be the reason for not losing the strength properties of the PM, GMAW joint and FCAW joint up to 300° C post fire condition. From the microstructural investigation after fire conditions (Figure 5-7), it is very clear that up to 300° C, the change in phase fraction of ferrite and carbide phases, change in average grain size are very meagre. But, when the post fire temperature increases from 300° C to 600° C and 900° C the change in reduction factor is considerably more. This could be attributed to the considerable change in grain coarsening and phase fraction of microstructural constituents i.e. the increased volume of ferritic phases and reduced volume of carbide phases.

There is one important distinguished observation from the PM and welded joints in post fire condition are described below. In PM up to 600° C, the grain size change and micro segregation of carbides are minimum, at 900° C, the grain coarsening is maximum, but without changing any morphology in this PM microstructure. But in both weld metals, up to 600° C, the grain size change and micro segregation of carbides are evident without changing the weld metals unique dendritic structure. This could be because of up to 0.3 to 0.5 Tm the possible microstructural changes during post fire condition are achievable by recovery. So, there could not be no appreciable microstructural changes, but, excessive point defect created will be absorbed by the grain boundary. So, the specimen fired up to 600° C, shown gradual reduction in YS and YTS properties. With maximum grain coarsening at 900° C, the entire change in morphological structure (i.e. dendritic to equiaxial) of weld metal. The reason for this great change in microstructure morphology shall be related to the allotropic change in α - iron / ferrite (BCC structure) to γ –iron / austenite (FCC structure), when the specimen was heated above 727° C to reach target temperature of 900° C [23]. This is also one reason that yield stress does not change significantly in specimens heated up to 600 °C and lower temperatures. The decrease in yield stress with increase in temperature at 900 °C results from transformation of austenite to equiaxial ferrite.
pearlite during subsequent cooling. Since, the PM and filler metals used in this investigation have enough carbon, so the potential formation of pearlite during cooling from 900°C is possible. Also the instrumented cooling method in this investigation offers slow cooling, naturally the formation of final microstructure for PM and both GMAW and FCAW weld metal cooling from 900°C, is normalized microstructure with some coarse ferrite pearlite [24].

4.0 CONCLUSIONS

A series of tests were conducted to measure the uniaxial tensile behaviour of S 355 J2 PM and butt welded connections made by using GMAW process and FCAW process. Post fire tests were performed at different temperatures likely ambient (25°C), 300°C, 600°C and 900°C. From this investigation the following conclusions were derived:

1. The morphological features like acicular ferrite (AF), polygonal ferrite (PF), grain boundary ferrite (GBF), Widmanstätten Ferrite (WF) are the similarities between GMAW and FCAW joints. But, inter lamellar spacing and width of the lamellae in WF, the availability and grain size of AF are the dissimilarities between these welds which duly decides the tensile behaviour of this joints

2. After fire, the residual properties of PM, GMAW and FCAW joints were follow the similar trends. At 300°C, the residual properties of YS, UTS and hardness shown a small increment, after 300°C, the trend follows a detrimental pattern in YS, UTS and hardness irrespective of the process used. The increment in strength and hardness properties at 300°C could be attributed to the strain hardening and blue brittleness effect of this PM and welded connections.

3. At 900°C, the reduction factor is minimum in PM, GMAW and FCAW joints. This could be related to the post fire microstructural changes and related hardness reduction. PM GMAW and FCAW joints all specimen shows coarse grain equiaxed ferrite pearlite microstructure.

REFERENCES

8. Daniele Forni, Bernardino Chiaia, Ezio Cadoni, Mechanical properties of s355 under extreme coupled effect of high temperatures and high strain rates, ECCOMAS Congress 2016, VII European Congress on Computational Methods in Applied Sciences and Engineering, 2016; 1-8

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Chemical composition (wt. %) of PM and filler metal used in this investigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element</td>
<td>C</td>
</tr>
<tr>
<td>Parent metal (S355 J2)</td>
<td>0.17</td>
</tr>
<tr>
<td>GMAW Electrode ER 70S-3 (Solid wire) BÖHLER EML 5</td>
<td>0.090</td>
</tr>
<tr>
<td>FCAW (Flux cored wire) BÖHLER AWS E71T1-M/C (BÖHLER TI 52-FD)</td>
<td>0.045</td>
</tr>
</tbody>
</table>
### Table 2  Mechanical properties of the PM and Filler wires used in this investigation

<table>
<thead>
<tr>
<th></th>
<th>Yield Strength - Y. S (MPa)</th>
<th>Ultimate Tensile Strength –UTS (MPa)</th>
<th>% Elongation</th>
<th>Impact Toughness (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parent metal (S355 J2)</td>
<td>384</td>
<td>527</td>
<td>26</td>
<td>82</td>
</tr>
<tr>
<td>GMAW Electrode ER 70S -3 (Solid wire) BÖHLER EML 5</td>
<td>550</td>
<td>630</td>
<td>22</td>
<td>60</td>
</tr>
<tr>
<td>FCAW (Flux cored wire) BÖHLER AWS E71T1-M/C (BÖHLER Ti 52-FD)</td>
<td>430</td>
<td>520</td>
<td>28</td>
<td>120</td>
</tr>
</tbody>
</table>

### Table 3  Welding conditions used for fabricating the joints

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>GMAW -(Solid wire)</th>
<th>FCAW -(Flux cored wire)</th>
</tr>
</thead>
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<tr>
<td>Filler wire diameter</td>
<td>mm</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Preheat temperature</td>
<td>°C</td>
<td>Nil</td>
<td>Nil</td>
</tr>
<tr>
<td>Interpass temperature</td>
<td>°C</td>
<td>135</td>
<td>135</td>
</tr>
<tr>
<td>Shielding gas (20% Ar + CO₂)</td>
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</tr>
<tr>
<td>Bead style</td>
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<td>stringer</td>
<td>stringer</td>
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<tr>
<td>Welding current</td>
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<td>152</td>
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<tr>
<td>Arc voltage</td>
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<td>23.3</td>
</tr>
<tr>
<td>Speed (mm/min)</td>
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<tr>
<td>Heat input</td>
<td>kJ / mm</td>
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<td>1.214</td>
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</table>

### Table 4  Residual tensile properties of PM

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Specimen Identification</th>
<th>YS (MPa)</th>
<th>Residual Factor</th>
<th>UTS (MPa)</th>
<th>Residual Factor</th>
<th>Fracture Location</th>
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<tbody>
<tr>
<td>25°C</td>
<td>PM1</td>
<td>405</td>
<td>101.25</td>
<td>546.01</td>
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<td>Reduced cross section</td>
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<td>490.99</td>
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<td>Reduced cross section</td>
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<td>PM2</td>
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<td>98.75</td>
<td>512.26</td>
<td>0.91</td>
<td>Reduced cross section</td>
</tr>
<tr>
<td>600°C</td>
<td>PM1</td>
<td>290</td>
<td>72.50</td>
<td>449.36</td>
<td>0.80</td>
<td>Reduced cross section</td>
</tr>
<tr>
<td></td>
<td>PM2</td>
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<td>73.75</td>
<td>471.26</td>
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<td>Reduced cross section</td>
</tr>
<tr>
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<td>PM1</td>
<td>290</td>
<td>72.50</td>
<td>449.36</td>
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### Table 5  Residual tensile properties of GMAW joint

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Specimen Identification</th>
<th>YS (MPa)</th>
<th>RF</th>
<th>UTS (MPa)</th>
<th>RF</th>
<th>Fracture Location</th>
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<tr>
<td>25° C</td>
<td></td>
<td>398.33</td>
<td>NA</td>
<td>538.58</td>
<td>NA</td>
<td>PM</td>
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<tr>
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<td>483.79</td>
<td>0.89</td>
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<td>566.78</td>
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<tr>
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<td>PM</td>
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<tr>
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<td>534.24</td>
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<td></td>
<td></td>
<td></td>
<td>IF</td>
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</table>

### Table 6  Residual tensile properties of FCAW joint

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<th>RF</th>
<th>UTS (MPa)</th>
<th>RF</th>
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</table>

(a) Joint configuration  
(b) Dimensions of the tensile specimen (All dimensions are in “mm”)

Figure 1 Joint configuration and specimen dimension
Figure 2  Photographs of post fire tensile tested specimen

(a) Post fire PM  (b) Post fire GMAW joint  (c) Post fire FCAW joint

Figure 3  Residual tensile behaviour of PM and welded connections of S 355 J2 structural steel
Figure 4 Comparison of hardness profiles of the welded joints at different temperatures

(a) GMAW joint

(b) FCAW joint

Figure 5 PM microstructure at different temperatures

(a) 25°C
(b) 300°C
(c) 600°C
(d) 900°C
Figure 6  Microstructures of GMAW joint FZ in as welded condition and after exposed at different elevated temperatures

Figure 7  Microstructures of FCAW joint FZ in as welded condition and after exposed at different elevated temperatures
EVALUATION OF STRUCTURAL INTEGRITY OF REPAIRED DYNAMICALLY LOADED ENGINEERING COMPONENT

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Abstract
The Moving beam of an 8000 Ton press had cracked during cold correction operation of a half shell of boiler drum of thickness 210 mm. A through crack was found to run vertically from the intersection point of the top flange towards the bottom flange at an angle of around 35 to 40 degree to the vertical. A detailed analysis and exhaustive investigation followed. To ascertain the structural integrity, an experimental stress analysis using strain gauges was performed after repair on this structure. Presently, the structure is working to its capacity. The rectification procedure adopted and the procedure for evaluation of structural integrity after repair have been described in this paper.

Key words: Weld repair, tensile residual stresses, compressive residual stresses, peening, dynamic loading, strain gauges, structural integrity.

1.0 INTRODUCTION
Repair and reclamation welding has always been a technological challenge and is of interest to fabrication engineers engaged in maintenance of production equipment. The after effects of repair and reclamation are very critical when the component is put into operation and need to be analyzed, as this may influence the performance and structural integrity. One of the major issues in reclamation welding during repair is the extent of the tensile residual stresses that are bound to develop in the weld and the material around the weld joint. These tensile residual stresses in combination with applied stress that is exerted during loading of the component could impair the usability. This is especially so when PWHT of the weld is not feasible. When the components are subjected to dynamic loading, the presence of compressive stress is beneficial as it tends to improve the fatigue life of the component. Though AWS structural welding code D 1.1 does call for the operation of peening that would impose compressive residual stresses over tensile residual stresses, the peening parameters are to be optimized before implementation.

The conventional NDT techniques like LPI, MPI and UT reveal the presence of any flaw but do not ascertain the structural integrity. In this study, the structural integrity was determined in a dynamically loaded repaired 8000 T press using strain gauges with associated instrumentation system. Prior to employing the strain gauge instrumentation system for structural integrity evaluation, the strain gauging procedure had been qualified. This paper highlights the repair carried out as well as the confirmatory checks on the structural integrity of the components to ensure continued usage.

2.0 REPAIR OF MOVING BEAM OF 8000 T PRESS
An 8000 Ton press frame had to undergo a major repair while in service. The moving beam of the Press is schematically represented as Figure 1.
An 800 mm width crack to the length of 2 meters in the moving beam had occurred. The repair had to be performed in-situ. The moving beam of the press had cracked during cold correction operation of a half shell of a boiler drum with thickness of 210 mm. The press has been working for the past 18 years. During operation, a long crack was seen with a big sound on the outer web plate of the Moving beam to a length of around 2 meters. The crack was running vertically from the intersection point of the top flange (supporting the cylinder and the slant plate connecting the top flange) towards the bottom flange at an angle of around 35 to 40 to the vertical plane, as shown in Figure 2.

During Ultrasonic testing, it was observed that the crack was a through crack and the plate thickness was seen displaced creating a pit like appearance on the surface. On further examination, few other cracks were also observed on the toe regions of the weld joining the slant plate nearer to the outer web plate and the top flange bearing the cylinder. In order to thoroughly investigate further, the weld joints on the rear side as well as on the other side of the cylinder were non-destructively tested. The tests revealed that cracks were on the joints between the middle slant plate and the top flange plate besides being present at the weld joint between the rear slant plate and the top flange. In all, there were six cracks noticed. Cracks had not been noticed in the other weld joints. As the moving beam weighs around 160 Tons and as there were no handling facilities in the Press shop to handle this weight, the repair had to be carried out in-situ without removing the beam from the press. The cracks could have been initiated by fatigue from the toe regions of the weld (where maximum tensile stresses are experienced) between the top flange and slant plate and this might have propagated in to the outer web plate with loading. The web plate appears to have ultimately failed due to shear as indicated by the angle at which crack occurred as well as by the presence of plastic deformation on the cracked surfaces of the plate. A detailed weld repair procedure was evolved and implemented. Peening operation was performed on the weld regions during and after repair, as the component was subjected to fatigue loading and stress relief heat treatment was ruled out.

3.0 LOAD TESTING OF THE BEAM AFTER REPAIR

In order to evaluate the structural integrity of the repaired beam, it was subjected to load test to a maximum of 8000 tons in a progressively increasing manner. During load testing, rosette type three element electrical strain gauges were fixed on the selected locations. The strain gauge locations are presented in Figure 3. Prior to employing the strain gauging method for structural integrity evaluation, a calibration test was conducted to confirm the proper functioning of the strain gauge along with the instrument used and to qualify the personnel employed for installing the strain gauges. Prior to testing, the beam was made free in all respects and its movement was checked thoroughly. Then the strain gauges were connected to the multi-point strain meter in quarter bridge mode. Prior to loading, the strain meter was zeroed under no-load conditions. Subsequently, a shakedown test at 2000, 4000 and 6000 Tons was done to check the instrumentation system and the performance of the gauges. After this, load test was carried out in steps starting from 2000, proceeding to 4000, 6000 and finally at 8000 Tons. The strain gauge
readings were recorded each time and checked for its magnitude. Subsequently, full load of 8000 Tons was applied three times on a dummy plate. Once again, the load test was carried out in steps to check if the behaviour of the cracked regions were linearly elastic. In all the locations, the strain vs. load trend was found to be linearly elastic, except in location 4, where a localized yielding was understood to have taken place due to repeated loading.

After the load test, magnetic particle testing was carried out in all the repaired locations to check for the presence of any cracks. This test revealed that the repair welded joints were free of flaws and were healthy.

Thus, this analysis indicated that the behaviour of the beam in the repaired regions is as good as that observed in the non-repaired regions.

4.0 RECOMMENDATIONS FOR FURTHER USE

In view of extensive weld repair, as a precautionary measure, it was recommended to use the 8000 T press at 60% of its rated capacity for a period of one week. As there were no cracks observed during this period, the repair work was deemed to have been complete and the press was permitted to operate to its full capacity.

REFERENCES

1. An over view of stress measurement techniques, N Raju., etal – WRI journal Volume 28, No. 3
2. Internal report on “Welding procedure adopted for rectification of cracked moving beam of 8000 Ton press” – Issued by WRI

![Figure 1](image-url)  
**Figure 1**  Schematic representation of 8000 Ton Press
Figure 2  Crack locations of 8000 Ton Press

Figure 3  Strain gauging locations for load testing of 8000 Ton Press, after repair