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A comparison of residual stresses in built-up steel beams using hole-drilling method †

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Abstract

Residual stresses have a significant effect on the stability resistance of metal building systems. An experimental program was conducted to measure these stresses in built-up steel beams using incremental hole-drilling method. The experimental results reveal that the predicted residual stress type of pattern for built-up I-sections with fillet welds on one side of the web is not the same as the pattern of residual stresses in built-up I-sections with fillet welds on both sides of the web.

Keywords: Beams; Residual stresses; Hole-drilling; Steel

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1. Introduction

Residual stresses are those stresses which already exist in a component before any external or service loads are applied. They may be present as a result of manufacturing and fabricating processes or they may occur during the life- time of the structure. Virtually, all manufacturing and fabricating processes including welding, casting, machining, molding heat treatment, etc., introduce residual stresses into the manufactured object. One of the key features of metal building systems is their primary frames being made up of built-up plate rigid frames. Steel plates are cut by using lasers or hydraulic-cutting machine into tapered shapes for webs and prismatic shapes for flanges. Then these shapes are placed into a ConRac submerged arc welder that welds both flanges to the web at one time. This weld is a fillet weld in one side of the thickness of the web. Residual stresses have a significant effect on the stability resistance of such structures. Engineers have paid special attention to develop several stress distribution forms for residual stresses based on the experimental or theoretical results.

These stress distributions can lead to malfunction in buckling problems of metal building structures, because the residual stress pattern for built-up beams with fillet weld on one side of the web is different from the residual stress pattern for built-up beams with fillet weld on both sides of the web. However, the purpose of this paper is to compare the residual stresses in built-up steel beams with fillet weld on one side of the web with the same built-up beams having fillet welds on both sides of the web using the hole-drilling method.

2. Materials and method

2.1 Material

Built–up I-section members used in this investigation were fabricated from continuous web and flange steel plates. The flange–to-web welds were under-

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matched and made with automatic submerged arc welding (AWS) process. A short beam for residual stress measurements was cut out from four built-up steel beams 5.5 meters long as shown in Fig. 1. Fillet weld of size 5 mm leg length was used for all specimens. All welding was performed in accordance with the American Welding Society (AWS) structural welding Code D1.1-2000 [1]. Residual stresses in the flanges and the webs were measured at three points (1, 2, and 3) for all specimens as shown in Fig. 1. The dimensions of the specimens are given in Table 1. Each specimen is referred to by a code number, such as A30, which denotes the specimen type A and depth, respectively. That is, A is the first group with single fillet weld on one side of the web, and its depth = 30 cm. The double letter AA is the first group with double fillet welds on both sides of the web).

The mechanical properties of the specimens were determined from standard tensile tests carried out on specimens prepared from the original plates. Thirteen coupons were prepared and tested in accordance with ASTM E8 Standard Test Methods and Definitions for Mechanical Testing of Steel Products [2]. The modulus of elasticity, E, Poisson's ratio, ν and yield stress, F_Y, used in the calculations, were 204 GPa, 0.29 and 374 MPa, respectively.

Table 1. Nominal dimensions of test specimens for residual stress measurement.

Specimen	d (mm)	b_f (mm)	t_f (mm)	t_w (mm)	L (mm)
A30	300	150	5	4	500
AA30	300	150	5	4	500
B40	400	150	6	5	500
BB40	400	150	6	5	500

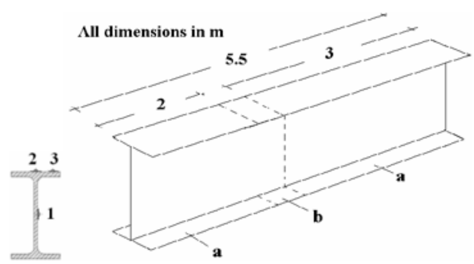

Fig. 1. Allotment of test specimens and locations of rosettes, a- for buckling test; b- for residual stress measurements.

2.2 Methods

A wide variety of residual stress measurement techniques exist, but the hole drilling strain-gage method, which belongs to semi-destructive methods, is the most popular and widely used technique for measuring residual stresses. Its popularity stems largely from its ease of use in many different application and materials, its limited damage to the specimen, and its general reliability. This technique has been quoted in ASTM Standard E837 since 1981. The hole-drilling method for measuring residual stress was first introduced by Mathar in the 1930s [3]. He measured displacements between two points across the drilled hole using mechanical and optical extensometers. Soete and van Crombrugge [4] employed a similar concept using electrical strain gages rosette type EA-09-125E around the hole rather than measuring changes in the hole diameter with an extensometer. Further work on measuring non-uniform residual stresses by hole-drilling method was performed by Schajer [5]. The method is empirical and depends on experimental calibration. Schajer [6] provided the first generalized finite element analysis of the hole-drilling method. Comprehensive practical information and further references are given in Technical Note TN-503-6 [7] supplied by Measurements Group, manufacturer of the specialized strain gage rosette shown in Fig. 2.

2.2.1 Principle of hole-drilling method

The hole-drilling method is based on the fact that drilling a hole in a stress field disturbs the equilibrium

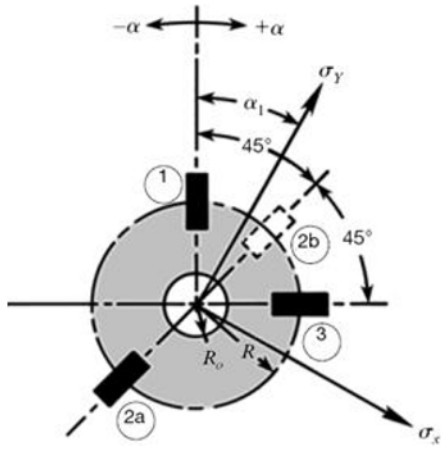

Fig. 2. Strain gage rosette arrangement for determining residual stresses (from Technical Notes TN-503-6).

of the stresses, thus resulting in a measurable deformation on the surface of the part, adjacent to the hole. Measurements of strains ε_1 , ε_2 , and ε_3 , in three different directions gage 1, gage 2 and gage 3 of a rosette, (Fig. 2) provide the necessary data for which the principal components σ_x and σ_y of the of the original residual stress state at hole location can be calculated.

For a linear elastic isotropic material, it may be shown theoretically that the following general formula relates the strain relaxation measured at any of the strain gages in the rosette in Fig. 2 to the principal residual stresses and the angle relative to the maximum principal stress direction [7]:

$$\varepsilon_r = A\left(\sigma_x + \sigma_y\right) + B\left(\sigma_x - \sigma_y\right)\cos 2\alpha_1 \quad (1)$$

where,

ε_r : measured strain relaxation

σ_y : maximum principal stress

σ_x : minimum principal stress

α_1 : angle measured counterclockwise from the nearer principal stress direction to the axis of strain gage no. 1.

A, and B - calibration constants.

In the present study, incremental hole-drilling was performed, since the stress to be determined was induced by welding, which causes a non-uniformly distributed residual stress below the material surface.

3. Experimental approach

The experimental results described here were obtained by using an EA-06-062RE-120 gage made with a gage circle diameter of 5.13 mm. The design of this rosette has a center pattern for precisely positioning the boring tool at the center of the gage. The gages were applied following the manufacturer's recommended procedure. The MANFORD VMC 610 machine with 6000 rpm was used for drilling the hole using a 2 mm central drill. The drilling was done in increments 0.05D up to a depth of 0.4D (Max depth for blind hole method as recommended by [2]), where D is the diameter of rosette. The data acquisition system was used to record strains. The instrumentation used in residual stress measurements is shown in Fig. 3.

To determine the effect of machining on the recorded strains, two coupons of dimensions 25 mm x 200 mm x 6 mm were cut from the original plates,

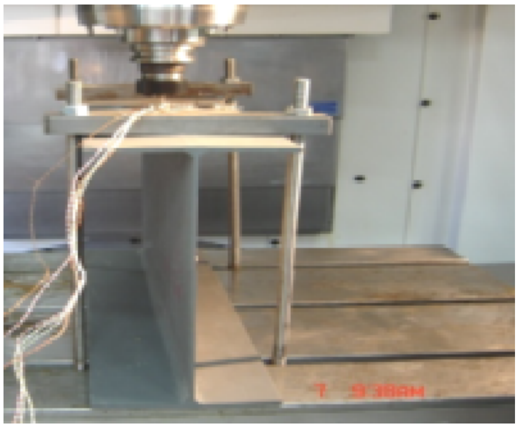

Fig. 3. Instrumentation of residual stress measurement.

stress-relieved at 680 °C, as per standard [1]. After hole drilling, the average strain readings were found to have little effect on residual stress calculations.

The incremental hole drilling data were analyzed by the principle of the integral method given by Schajer [5]. In the integral method, the contributions of the total measured strain relaxations of the stresses at all depths are considered simultaneously. This provides a separate evaluation of residual stresses within each increment of depth.

4. Experimental results

Table 2 shows the measured relieved strains via incremental hole-drilling for specimen B40 at point 1 to a depth of 2 mm. The maximum and minimum principal stresses can be calculated through the thickness using the integral method. The average measured values were used to represent the residual state of the tested specimens and are summarized in Table 3.

For specimens with fillet weld on one side of the web, the heat imparted to the plates during welding process is smaller than that of specimens with fillet weld on both sides. Away from the weld, compressive stresses are developed to maintain a state of equilibrium. The magnitude of compressive residual stresses at flange tips for specimen A30 is higher than that of specimen B30. The welding residual stresses in the area of the cross section away from the weld are higher in thinner welded shape than those found in thicker plates. This finding agrees with [8, 9 and 10]. A significant portion of the web is in residual compression

For specimens with fillet weld on both sides of the

Table 2. Measurements of residual stress by the hole-drilling method for specimen B40 at Point 1. $I = (\varepsilon_3 + \varepsilon_1)/2$, $II = (\varepsilon_3 - \varepsilon_1)/2$, and $III = (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)/2$.

Z/D	Measured strain μ_ε	I	II	III	Stresses	
					σ_{min} MPa	σ_{max} MPa
0.05	-5	-3.5	1.5	1.5	38.47	15.27
	-5					
	-2					
0.10	-7	-11	-4	2	77.22	16.61
	-13					
	-15					
0.15	-2	-9	-7	8	-7.19	-70.09
	-17					
	-16					
0.2	5	-9.5	-14.5	13.5	44.98	-42.81
	-23					
	-24					
0.25	6	-10.5	-16.5	13.5	18.54	-5.96
	-24					
	-27					
0.30	6	-10	-16	14	-4.33	-32.13
	-24					
	-26					
0.35	12	-6	-18	16	-86.12	-129.32
	-22					
	-24					
0.40	16	-2.5	-18.5	19.5	-59.06	-129.37
	-22					
	-21					
Average					**2.81**	**-47.22**

Table 3. Experimental results of residual stresses.

Specimens	Point 1 MPa	Point 2 MPa	Point3 MPa
A30	-77	228	-204
AA30	-81	355	204
B40	-47	301	-191
BB40	-121	320	162

web, the whole flange may have tensile residual stresses. The magnitude of tensile residual stresses at the center flange for specimen BB30 is lower than that AA30. For heavier shapes, the weld makes up a smaller percentage of the total area. The heat input per unit volume is reduced; the magnitudes of residual stresses would be lower. This finding agrees with [11]. The center of both webs is in residual compression. The flange tips also contain tensile stresses. In general, the second pass caused the residual stresses to be higher in tension in the flange center.

From the experimental results shown in this table, the value of the tensile residual stress in specimen AA30 at the web flange juncture is 55% higher than that of specimen A30, and that of specimen BB40 is 6% higher than that of specimen B40, indicating that the second welding pass imparts an increase of 31% on average for specimens with fillet welds on both sided of the web. The flange residual pattern in specimens A30 and B40 (with fillet weld on one side of the web) has a high residual compression in the flange tips, while the flange residual pattern in specimens AA30 and BB40 (with fillet weld on both sides of the web) has tensile stresses.

5. Conclusion

The predicted residual stress type of pattern for the present built-up I-sections with fillet welds on one side of the web is characterized by very high tensile stresses near the web flange welds balanced by compression elsewhere. A significant portion of the web is in residual compression. For specimens with fillet welds on both sides of the web the residual stress pattern is different because the whole flange may have tensile residual stresses.

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