Металлофиз. новейшие технол. / Metallofiz. Noveishie Tekhnol.
2015, т. 37, № 9, сс. 1325–1338
Оттиски доступны непосредственно от издателя
Фотокопирование разрешено только
в соответствии с лицензией

ФИЗИКА ПРОЧНОСТИ И ПЛАСТИЧНОСТИ

PACS numbers: 06.60.Vz, 61.72.Hh, 62.20.F-, 81.20.Vj, 81.40.Lm, 81.70.Bt, 83.50.Uv

Investigation and Characterization of Residual Stress on Prestressed Steel I-Beams Manufactured by Welding

A. Özer and Yu. Özçatalbaş*

Gazi University,
Technical Sciences Vocational School,
06935 Ostim Yenimahelle, Ankara, Turkey
**Gazi University,*
Faculty of Technology,
Department of Metallurgy and Materials Engineering,
06500 Besevler, Ankara, Turkey

The purpose of this study is to determine type and magnitude of residual stresses occurring on steel I-beams, which are manufactured by using prestressing with welding method. In order to achieve this purpose, 50, 100, 150, 200 and 272 MPa prestressed steel I-beams (PSIB) are manufactured. Residual stresses on these beams are determined with the hole-drilling method. As determined, the longitudinal residual tensile stress increases with increasing prestressing stress up to 200 MPa. As also detected, the residual tensile stress up to 92 MPa on crosscut in surface centre of lower flange occurs, and it converts to residual compressive stress through edges of lower flange. Moreover, residual compressive stress is determined at web of beam. This stress converts to tensile stress on lower flange, and this variability on stress type creates shearing stress on welding seam.

Key words: welding, prestressed steel beam, residual stress, hole-drilling method.

Мета цієї роботи — визначити тип та величину залишкових напружень, які виникають у сталевих двотаврових балках, виготовлених з використанням методи зварювання з попереднім напруженням. Для досягнення цієї мети було виготовлено сталеві двотаврові балки з попереднім напруженням у 50, 100, 150, 200 і 272 МПа. Залишкові напруження в цих бал-

---

Corresponding author: Alpay Özer
E-mail: alpiozer@gmail.com

A. Özer and Yu. Özçatalbaş,
Investigation and Characterization of Residual Stress on Prestressed Steel I-Beams Manufactured by Welding, *Metallofiz. Noveishie Tekhnol.*, **37**, No. 10: 1325–1338 (2015).

ках визначалися методою свердління отворів. Було встановлено, що поздовжнє залишкове розтягувальне напруження зростає зі збільшенням попереднього напруження аж до 200 МПа. Було також виявлено, що виникає залишкове розтягувальне напруження аж до 92 МПа на поперечному перерізі в центрі поверхні нижнього фланця, і воно перетворюється в залишкове напруження стискання через краї нижнього фланця. Крім цього, залишкове напруження стискання визначалося біля стінки балки. Це напруження перетворювалося в розтягувальне напруження на нижньому фланці, й така варіябельність типу напруження створює напруження зсуву на зварному шві.

Ключові слова: зварювання, попередньо напружена сталева балка, залишкова напруга, метода свердління отворів.

Цель данной работы — определить тип и величину остаточных напряжений, возникающих в стальных двутавровых балках, изготовленных с использованием метода сварки с предварительным напряжением. Для достижения этой цели были изготовлены стальные двутавровые балки с предварительным напряжением 50, 100, 150, 200 и 272 МПа. Остаточные напряжения в этих балках определялись методом сверления отверстий. Было установлено, что продольное остаточное растягивающее напряжение возрастает с возрастанием предварительного напряжения вплоть до 200 МПа. Было также обнаружено, что возникает остаточное растягивающее напряжение вплоть до 92 МПа на поперечном разрезе в центре поверхности нижнего фланца, и оно преобразовывается в остаточное напряжение сжатия через края нижнего фланца. Кроме того, остаточное напряжение сжатия определялось у полки балки. Это напряжение преобразовывалось в растягивающее напряжение на нижнем фланце, и такая вариабельность типа напряжения создаёт напряжение сдвига на сварном шве.

Ключевые слова: сварка, предварительно напряжённая стальная балка, остаточное напряжение, метод сверления отверстий.

(Received July 15, 2015)

1. INTRODUCTION

Prestressing is application of residual stress deliberately to a construction element in order to increase its strength under various working loads. The term of prestressing is first used for reinforced concrete constructions. However, there have been ongoing studies on providing steel construction elements with advantages of prestressed construction elements in reinforced concrete constructions, such as low deflection under service loads, high elastic behaviour under high loads and high resistance.

Until now, by applying different prestressing techniques, various prestressed steel beams have been manufactured and patented. Most of studies conducted on this subject aim to create residual compressive stress on lower flange of beam with guy lines from outside. Elements manufactured with this technique are denominated as ‘external prestressed steel construction elements’ [1–3].

In studies conducted in recent years, however, internal prestressed steel I-beam has been manufactured using different techniques. In the study conducted by Özçatalbaş and Özer [4], they manufactured internal prestressed steel I-beam (IPSIB) by joining the steel lower flange plate, to which prestressing was applied within elastic limits, and T-profile with help of welding. Authors applied flexural test to the prestressed steel I-beams, which were fabricated using this technique. They emphasized that the stress distribution formed on upper and lower flanges show resistance to flexural load applied on beam. Therefore, it was stated in the test results that flexural strength of prestressed steel I-beams is increased by approximately 30% compared with that of non-prestressed beams.

Chapeau [5], on the other hand, positioned two T-profile bodies by creating I-section in order to produce internal prestressed steel beam. Then, load was applied in such a way to create predeflection to bending load and they were joined by welding. Therefore, prestressed steel I-beam was manufactured.

Kim *et al.* [6] applied a different method to manufacture prestressed steel I-beam. In that study, a new method called as ‘multi-stepwise thermal prestressing method (M-TPSM)’ was used. In this method, plate heated using electromagnetic heat source was fixed to beam with high-strength bolts so as to come into contact with beam. Dimensional contraction occurring with cooling in plate created prestressing on beam. After the static loading tests, it was detected that the prestress formed in beams increases the load carrying capacity of the beam. Therefore, the fact that there occurs less deflection in a prestressed beam than a non-prestressed beam is emphasized as an important advantage of the prestressed beam.

In addition to manufacturing of prestressed steel beam, a number of studies on strengthening of current steel structures with application of prestressing have also been conducted. Adhesive bonding/joint of prestressed laminates to steel structures can be given as example for this method [7]. In this method, prestressed-applied carbon fibre reinforced polymer (CFRP) is adhered to lower surface of steel beam by means of laminate adhesive bonding. After carrying out adherence, prestressing applied to CFRP laminate is removed. This way prestressed steel beam is fabricated. Compressive prestressing force, F, is formed by removal of prestress force applied on CFRP-laminate. The moment occurring as a result of prestress force will form compressive stress on lower flange and tensile stress on upper flange. Thus, stress distribution formed on beam due to the effect of prestress force will increased the load carrying capacity of the beam.

Narmashiri and Jumaat [8] examined linear and non-linear analysis of steel plates and CFRP reinforced steel I-beams in 2*D* and 3*D* with finite elements method. They stated that the load carrying capacity of beam is increased particularly in the plastic region and lateral torsional-buckling is diminished as the thickness of strengthening laminates, which are used in steel I-beam, is increased.

Although prestressed steel I-beam manufacturing studies have been conducted by using different techniques, there is no study in the literature that focuses on characterization of residual stress on prestressed beams manufactured. In addition to this, condition of residual stress is quite important in prestressed steel beams. The purpose of this study is to conduct characterization of residual stresses on prestressed steel I-beams.

As a result, manufacturing internal prestressed steel I-beam with welded joint method as the experimental element, measuring of residual stresses, which the welded joint creates on beams together with prestressing using the hole-drilling method and analysing results were conducted in this study.

2. EXPERIMENTAL

Prestressed I-beam manufacturing with welded joint. Steel plate with 50×5 mm^2 cross-section and semi-finished steel T-profile with $50\times50\times5$ mm^3 cross-section were used to manufacture steel I-beam. Table illustrates mechanical properties used in the experiments.

Prestressed I-beam manufacturing is conducted using the method developed by Özçatalbaş and Özer [4, 9]. Test setup is used to fabricate internally prestressed steel I-beam as shown in Fig. 1. In order to manufacture prestressed steel I-beams according to this method, 50, 100, 150, 200 and 272 MPa prestressings were applied to lower flange steel plate, which would create lower flange of the beam, within elastic limits. T-profile was joined to lower flanges, on which tensile prestressing was applied, using gas metal arc welding (GMAW) method. Therefore, internal prestressed steel I-beams and non-prestressed I-beams were

TABLE. Mechanical properties of experimental materials.

Material	Yield stress σ_y, MPa	Tensile stress σ_t, MPa	Elongation, %
Steel plate (lower flange) (EN 10025)	372	459	29
T-profile (EN 10025)	376	465	24

produced. In order to remove effects of residual stresses that would occur due to welded joining, some of non-prestressed I-beams underwent the stress relief heat treatment at 630°C for 1 hour.

Determining residual stresses on beams with prestressing. As illustrated in Fig. 2, it was planned to conduct residual stress measurements in eight points (MP) on beams. However, approximately same values were obtained on MP1 and MP2 coded measurement points on beams manufactured with 200 MPa prestressing in which maximum

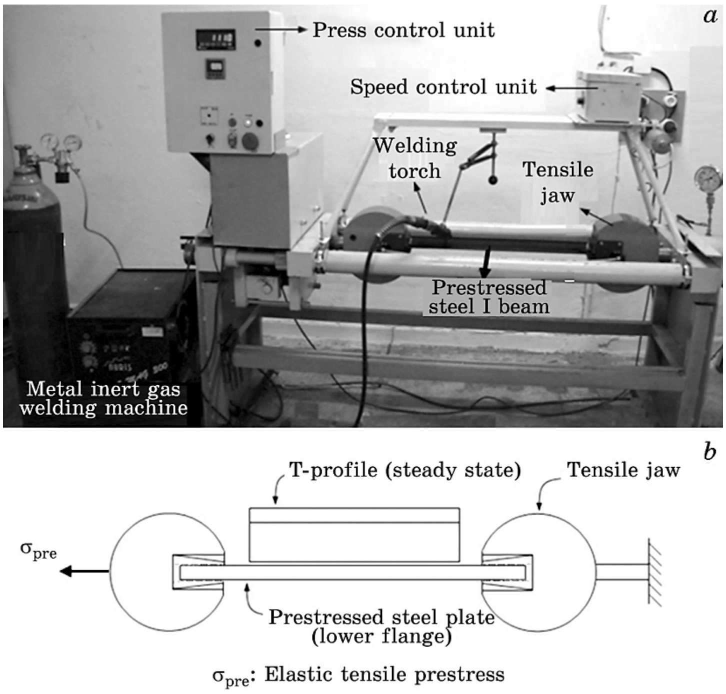


Fig. 1. Test set-up (*a*), schematic illustration (*b*).

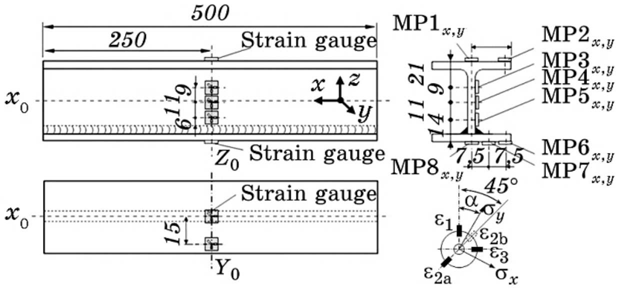


Fig. 2. Residual stress measurement points on beams and strain gauge rosette arrangement.

predeflection occurred (max. stress difference 4 MPa). The fact that residual stress has similar magnitudes on these two measurement points is interpreted such that only prestressing had an effect on residual stresses on this region as upper flange of beam is far away from weld zone. Therefore, residual stress measurements were taken only on MP1 coded point in upper flanges of other beams.

In measurements of residual stress, rosette strain gauges (RSG) coded as EA-06-062RE-120 by the producing firm are used. Drilling processes are conducted at the pressure of 276 kPa using a RS-200 high-speed air turbine that reaches to ≅300000 rpm rotation speed [10]. Along with commencement of drilling processes on beam, strain data are taken in με by strain indicator. Afterwards, obtained data are analysed using H-drill analyser software [11].

Residual stress measurements conducted in three stages. Firstly, measurement on $MP8_{x,y}$ is taken on the beam to which stress relief heat treatment is applied at 630°C. During the second stage, residual stresses are measured on $MP1_{x,y}$ and $MP8_{x,y}$ of all other beams. In the third stage, residual stress is measured on other measurement points of non-prestressed, 200 MPa and 272 MPa prestressed beams.

3. RESULTS AND DISCUSSION

After stress relief heat treatment, residual stress measured is $\sigma_{max} = 0$, $\sigma_{min} = -2$ MPa on non-prestressed beam. According to obtained data of residual stress, residual stresses that occurred on non-prestressed beams using the welded joint are removed with heat treatment applied.

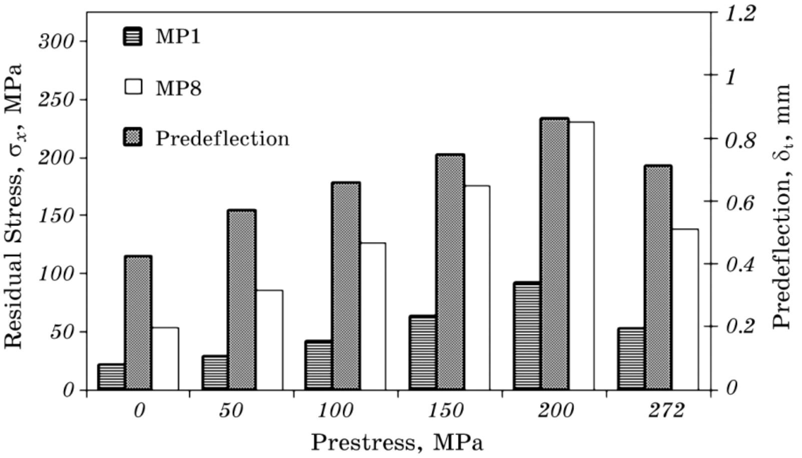


Fig. 3. Residual stresses in direction of x on MP1 and MP8 and change in predeflection due to residual stress.

Stress relief heat treatment is based on reduction of yield stress of the material with increasing temperature [12–15].

Quantity of prestressing on graph of Fig. 3 illustrates changes in predeflection due to residual stress and residual stresses in x direction, taken from MP1 and MP8. Predeflections occurring with increasing quantity of prestressing applied on beams and residual stresses increased up to beam manufactured by applying of 200 MPa prestressing. On beam manufactured with 272 MPa prestressing, it may be said that residual stresses and correspondingly predeflection reduced due to partial plastic yield as a result of heat generated during welded joint.

Figure 4 illustrates residual stresses measured on MP1 point. Increasing residual tensile stresses (σ_x) with prestressing increasing up to 200 MPa in the x direction, and increasing residual compressive stresses (σ_y) in the y direction were determined. Stress distribution on upper flange is generated with the effect of moment (predeflection) generated due to applied prestressing and welded joint. Figure 4 illustrates that $\sigma_{\max}$ and σ_x stresses, and $\sigma_{\min}$ and σ_y stresses give considerably similar values. Therefore, residual tensile stresses in the direction of x and y are major and minor principal stresses. For this reason, axial residual stresses may exist on upper flanges of beam.

Figure 5 illustrates residual stresses generated on MP8. $\sigma_{\max}$ and σ_x stresses and $\sigma_{\min}$ and σ_y stresses gave close values. However, proximity between stress values is not as much as on MP1, because residual stresses generated on lower flange with the effect of welded joint are more effective in comparison to upper flange, which was distant from welding seam. According to data of H-drill analysis, angle between $\sigma_{\max}$ and σ_x residual stresses is approximately −19°. The reason for this angular difference may be caused by torsional effect generated due to ir-

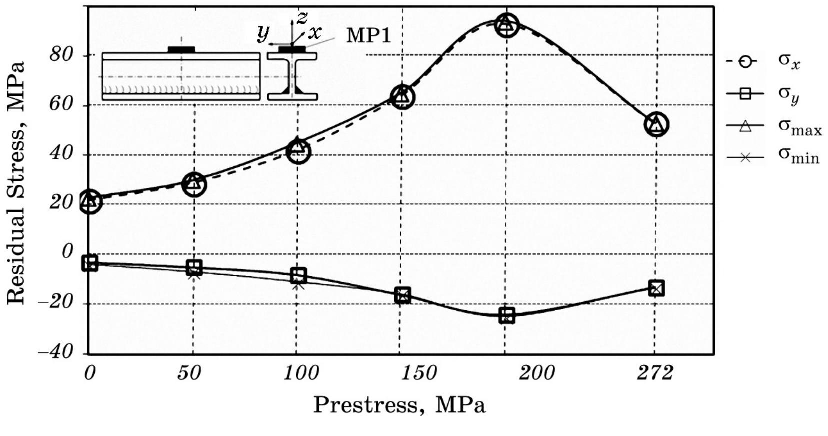


Fig. 4. Residual tensile and compressive stresses on MP1.

regularity in welding seam because accumulation of seams to lower flange plate or beam web was not homogenous although internal edge welding seams were made using a robotic GMAW system. This irregular accumulation on seams (< 1/5 mm) affects distribution of residual stresses and can generate torsional effect in beams.

Figure 5, on the other hand, illustrates changes in σ_x and σ_y residual stresses on MP8 due to prestressing and welded joint. Generation of residual tensile stresses based on the prestressing increasing up to 200 MPa in the x direction was determined. Due to existence of residual tensile stresses on upper flanges of the beam in the direction of x, it may be thought that there should be residual compressive stresses on lower flanges in the direction of x. The matter that should be given attention here is the effect of welded joint and applied prestressing on residual stresses. In welded T-joints, generation of residual tensile stress on lower area of welding seam in the direction of x is inevitable. The reason for this situation is shrinkage effect of welding metal based on melting and solidification combinations generated during welded joint [16, 17].

In beam manufactured with welded joint without applying prestressing, residual tensile stress of 53 MPa was determined on MP8 in the direction of x. In their study on T-joint, Barsoum and Lundback [18], presence of residual tensile stress of nearly 75 MPa on middle point of lower flange was determined as a result of residual stress measurement tests conducted with X-ray diffraction. The important matter, apart from difference of 22 MPa caused from different welding parameters or construction, is the residual tensile stress that welding seam generates under lower flange.

In beams manufactured with application of prestressing, lower

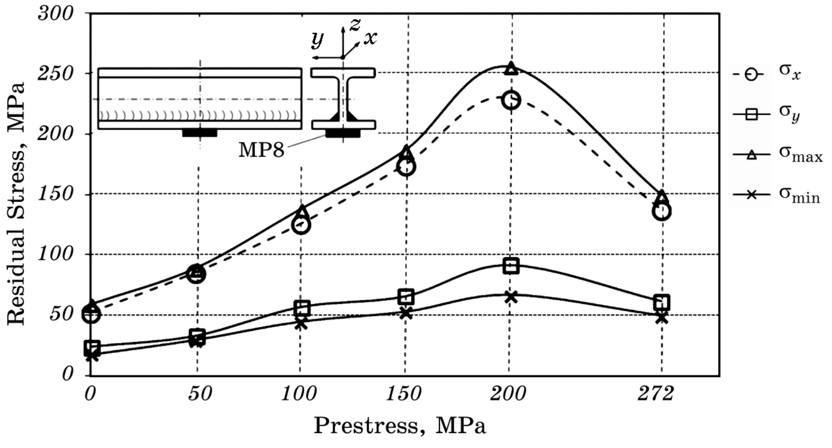


Fig. 5. Residual tensile stresses on MP8.

flanges of the beam try to apply compressive stress to T-profile by removing prestressing applied after welded joint. T-profile, on the other hand, displays resistance against this compressive stress. As a result, lower flange plate to which prestressing is applied remain under influence of residual tensile stress in the direction of x with the effect of welded joint and applied prestressing (Fig. 5).

It is determined that residual stresses on the lower flange in the direction of y increased in the direction of tensile along with the prestressing increasing up to 200 MPa (Fig. 5). Since residual stresses in the direction of x on the lower flange are tensile stresses, it may be thought that residual stresses in the direction of y should be compressive stress. However, residual tensile stresses occur in the direction of y due to thermal cycles generated during welded joint [14]. Moreover, angular distortions generated on lower flange in double sided internal edge weldings cause residual tensile stress on centre line (y-axis) latitudinal to lower surface of lower flange [16, 19, 20]. Another matter that should be considered is that with increasing prestressing, quantity of the residual tensile stress generating in direction of y increases.

Figure 6 illustrates that σ_x residual stresses generating on MP8 are greater than σ_x residual stress generating on MP1. The $\sigma_x = 53$ MPa on MP8 and $\sigma_x = 22$ MPa on MP1 determined in non-prestressed beams are the residual stress values. These residual stresses are the stresses generated only by welding seam. In addition to this, the reason for residual stresses higher than prestressing applied in lower flange is common effect of welding joint and applied prestressing. Residual tensile stresses reducing to 138 MPa on lower flange plate of the 272 MPa prestressed beam demonstrated that plastic deformation in the material occurred during welded joint process with this prestressing.

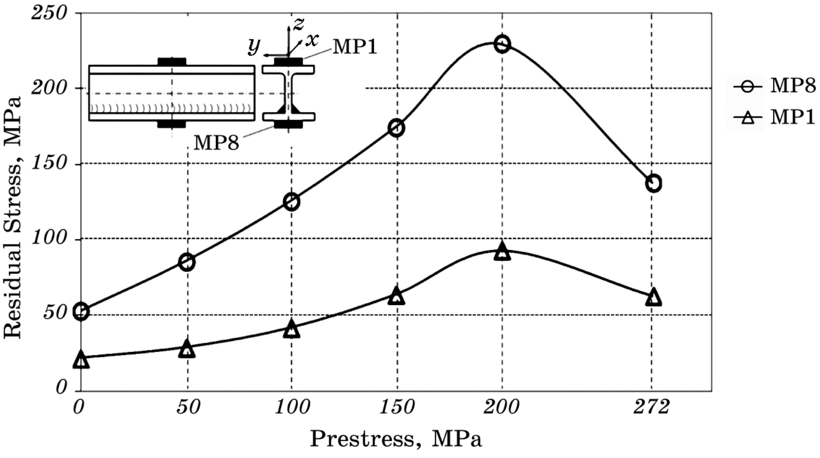


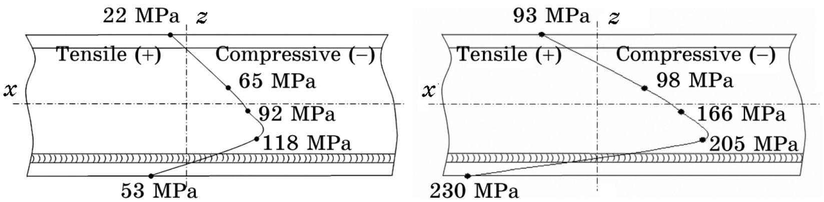
Fig. 6. The σ_x residual stresses in MP1 and MP8.

In order to characterize residual stresses generating due to prestressing in I-beams, residual stress was also measured on MP3, MP4, MP5, MP6, and MP7 measurement points in beams with 200 MPa, 272 MPa prestressed and non-prestressed beams. Figures 7 and 8 illustrate results of measurements.

Figure 7 illustrates type and magnitude of σ_x residual stresses after measurements on MP1, MP3, MP4, MP5 and MP8 points. In all beams, there were residual tensile stresses on MP8 in the direction of x–x. These stresses are generated by the effect of welding joint and especially applied prestressing. The effect of prestressing can be explained as that return of elongation generated by elastic tensile stress on lower flange is not allowed by welding seam of T-profile.

Figure 7 illustrates that the σ_x residual stresses on beam webs are stresses in terms of compressive as a result of measurements conducted on MP3, MP4, and MP5 points. The reason for generation of residual compressive stress on non-prestressed beam web is welding joint (Fig. 7, *a*). Due to cooling after welded joint process, the welding seam would try to shrink based on shrinkage effect of welding seam. This situation would lead to generation of residual tensile stresses throughout welding seam. Due to tensile stress throughout axis of the seam, high residual compressive stresses generated in areas near seam on beam web and residual compressive stresses decreased as moved away from the seam.

In prestressed beams, on the other hand, this situation is different

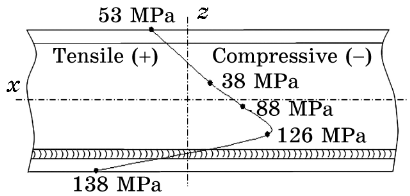


Non-prestressed beam

a

200 MPa prestressed beam

b



272 MPa prestressed beam

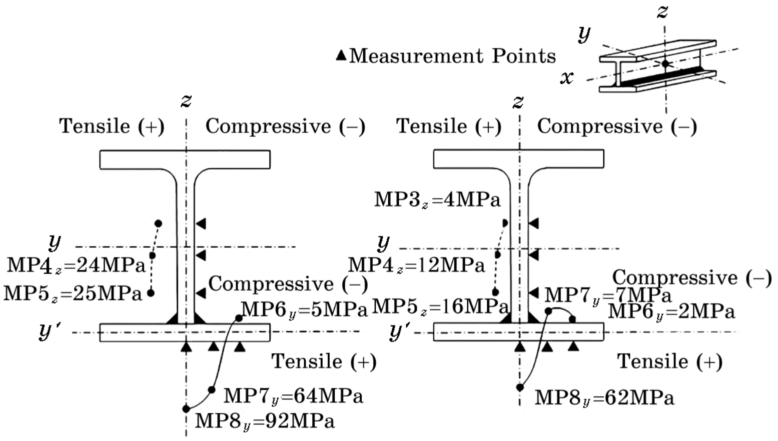
c

Fig. 7. Residual stresses in direction of x–x on upper/lower flanges and web of beams.

and higher residual compressive stresses generated the on beam web (Fig. 7, *b*, *c*). It is caused by the fact that residual stresses on prestressed beam webs are generated with welding joint and applied prestressing. Welding seam of T-profile prevents return of axial and elastic tensile stress generated on lower flange with prestressing. In this case, tensile stress applied to lower flange applies the compressive stress to T-profile due to elastic recycle. This residual compressive stress due to prestressing combines with residual compressive stress caused by welding joint and as a result, causes generation of high residual compressive stresses on beam web. Another important matter is also that T-profile displays resistance against residual compressive stress which lower flange applies to T-profile. In this case, T-profile, with its resistance, causes residual tensile stress at high rate on lower flange. As a result, what transmits high residual tensile and compressive stresses to lower flange and T-profile is the welding seam, and therefore welding seam is exposed to shearing stress (Fig. 7, *b*, *c*).

Figure 7, *c* illustrates results obtained in 272 MPa prestressed beam in which plastic yield occurs due to applied prestressing. Generation of residual stresses are characteristically the same as that of 200 MPa prestressed beam. However, generated stress values are lower. Due to plastic yield that occurs on lower flange because of the effect of heat generating, welded joint reduces desired residual stresses in the beam.

Figure 8 illustrates residual stresses in directions of y–y and z–z on cross-sections of beams with 200 MPa and 272 MPa prestressing. Dashed lines in the figure illustrate residual stresses (MP3, MP4, and MP5) on cross-section of beam in the direction of z–z; on the other



200 MPa prestressed beam 272 MPa prestressed beam

a *b*

Fig. 8. Residual stresses in direction of y–y and z–z in beams.

hand, straight lines illustrate residual stress measurement results in the direction of y–y taken from MP6, MP7, and MP8 on the lower flange. While residual stress distribution in the direction of y–y on lower flanges of both two beams is in the form of tensile stress on MP8, it converts into compressive stress through the flange edge (on MP7 and MP6).

In beams, residual tensile stress at high rate is determined in direction of y–y on MP8 with the effect of welded joint and applied prestressing. Figure 8 illustrates that, on MP8, residual tensile stress occurring in beam with 200 MPa prestressing is greater than residual tensile stress in beam with 272 MPa prestressing. It may be stated that plastic yield generating on the lower flange plate due to high temperature during welded joint causes low residual tensile stress on the lower flange centre of the beam with 272 MPa prestressing.

It is determined that residual tensile stress occurs in beams in the direction of z–z. Beam web is exposed to residual compressive stress in the direction of x–x with the effect of prestressing. Prestressing forces applied to beams create axial stress condition in beams. Hence, residual tensile stresses are determined in direction of z–z vertical to residual compressive stresses in the direction of x–x.

Figure 9 illustrates residual stress measurement results in the direction of x–x taken from MP6, MP7 and MP8 points on the graph. Measurement results of non-prestressed beam reveal that residual tensile stresses generated on areas near seam ($MP8_x$) converted into residual compressive stresses as moved away from the seam ($MP7_x$, $MP6_x$). This stress distribution in non-prestressed beam is a typical residual stress distribution generated with the effect of welded joint [14, 19, 20]. Stress distributions generated in 200 MPa and 272 MPa prestressed beams show similarity. Existence of residual tensile stress with the effect of prestressing applied in lower flanges of the beam is

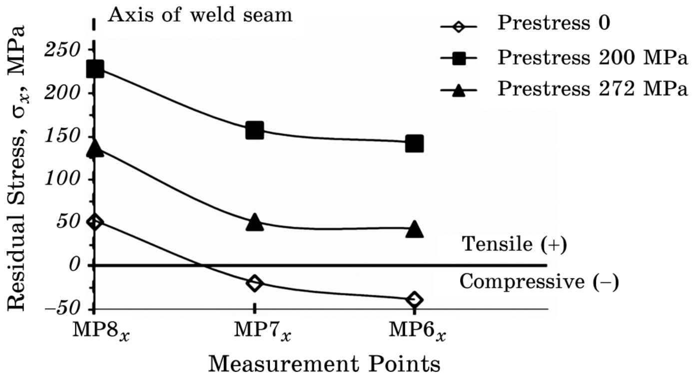


Fig. 9. Residual stresses in direction of x–x on MP6, MP7 and MP8.

in question. However, magnitude of residual tensile stress reduces from centre to edge ($MP8_x$, $MP7_x$, $MP6_x$). Presence of high tensile residual stresses on area of welding seam, where prestressing is transmitted to T-profile, displays natural stress distribution.

4. CONCLUSIONS

Results obtained in this study aiming to characterize residual stresses that occur with the effect of prestressing and welded joint on prestressed steel I-beams manufactured with method of welded joint, using the hole drilling method, are summarized as the following:

It is found out that axial residual tensile stress occurred on lower flanges of the beam together with prestressing increasing up to 200 MPa.

Non-axial (−19° deviation) complex stress distribution caused by irregularity of welding seam is determined on lower flanges.

Tensile stress on lower area of welding in direction of y–y axis on lower flanges of beams and residual stress distribution in form of compressive on edge of the flange is observed.

It is found out that magnitude of residual stress vertical to beam axis (y–y) and on the centre of lower surface of lower flange manufactured with 200 MPa prestressing is greater than stress value occurring on non-prestressed and 272 MPa prestressed beams.

Residual tensile stress distribution is formed in the direction of (z–z) on webs of prestressed beams. Furthermore, on beam web, residual compressive stresses occurred as longitudinal (x–x direction) to beam increasing from upper flange to prestressed lower flange up to 200 MPa.

Residual tensile stresses existed on lower flange of the beam and in direction of prestressing (x–x) together with prestressing increasing up to 200 MPa. In prestressing higher (272 MPa) than this, residual tensile stress value decreased.

The authors thank Gazi University for the financial support of this research work (07/2009-21).

REFERENCES

1. J. M. Park, *Prestressed Steel Beam*, Korean Patent No. KR2002071611 (2002).
2. H. Zhaobo, *Prestressed Large-Span Solid Portal Steel Frame and its Construction Process*, Patent No. CN1335439 (2002).
3. K. Tomoyasu, *Prestressed Steel Framed Beam*, Patent No. JP7145655 (1995).
4. Y. Özçatalbaş and A. Özer, *Materials and Design*, No. 28: 6 (2007).
5. W. Chapeau, *Manufacture of Prestressed Steel Beam*, Patent No. GB2190611 (1987).

6. S.-H. Kim, J.-H. Ahn, C.-Y. Jung, and J.-H. Kim, *J. Constructional Steel Research*, No. 65: 7 (2009).
7. A. Björklund and J. Höglind, *Strengthening of Steel Structures with Bonded Prestressed Laminantes* (Thesis of Disser. for MSc) (Göteborg: Chalmers University of Technology: 2007).
8. K. Narmashiri and M. Z. Jumaat, *Simulation Modelling Practice and Theory*, No. 19: 1 (2011).
9. Y. Özçatalbaş and A. Özer, *Manufactured Internal Prestressed Steel I-Beam*, Patent No. TR200400366 (2004).
10. *Vishay Micro-Measurement Tech-Note*, Document No: 11304 (2011).
11. A. Özer and Y. Özçatalbaş, *J. Fac. Eng. Arch. Gazi Univ*, No. 26: 3 (2011).
12. N. Özden, *Heat Treatment of Welding* (Istanbul: Nurettin Uycan Inc.: 1985) (in Turkish).
13. *Handbook of Aluminum. Residual Stress and Distortion* (Eds. E. G. Totten and D. S. S. Mackenzie) (New York: Marcel Dekker, Inc.: 2003), vol. **1**, p. 305.
14. R. W. Messler, *Principles of Welding* (New York: John Wiley and Sons Inc.: 1999), p. 206.
15. *Handbook of Residual Stress and Deformation of Steel, Material Factors* (Eds. G. Totten, M. Howes, and T. Inoue) (Materials Park, Ohio: ASM International: 2002).
16. T. L. Teng, C. P. Fung, P. H. Chang, and W. C. Yang, *Int. J. Pressure Vessels and Piping*, No. 78: 8 (2001).
17. H.-Y. Lee, F. R. Biglari, R. Wimpory, and K. M. Nikbin, *Engineering Fracture Mechanics*, No. 73: 13 (2006).
18. Z. Barsoum and A. Lundback, *Engineering Failure Analysis*, No. 16: 7 (2009).
19. A. Çalık, *Elektron Işın Kaynağı İle Birleştirilmiş İki Farklı Çelik Malzemenin Kaynak Bölgesinin İncelenmesi* [Investigation of Welding Zone of Dissimilar Steel Materials Joined Electron Beam Welding] (Thesis of Disser. for Dr. Materials Sci.) (Isparta: Süleyman Demirel Universty: 2004) (in Turkish).
20. *Metals Handbook. Welding, Brazing and Soldering* (Eds. D. V. Olson, T. A. Siewert, S. Liu, and G. R. Edwards) (Ohio: American Society of Metals: 1983), vol. **6**.