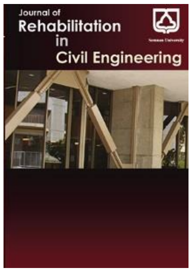
Journal of Rehabilitation in Civil Engineering 11-2 (2023) 01-17



Journal homepage: http://civiljournal.semnan.ac.ir/

Material Effects on Tangent Modulus of Steel Square Hollow Section

Seyed Mohammad Reza Mortazavi[1*], Milad Shakiba[1*], Behrouz Zaeimdar[1]

1. Department of Civil Engineering, Shahid Rajaee Teacher Training University, Tehran, Iran
Corresponding authors: *mortazavi@sru.ac.ir* (S.M.R Mortazavi), *m.shakiba@sru.ac.ir* (Milad Shakiba)

ARTICLE INFO

Article history:
Received: 15 November 2016
Revised: 20 April 2022
Accepted: 23 April 2022

Keywords:
Prestraining;
Strain ageing.
Finite element;
Material effects;
Modulus of elasticity;
Square hollow section;
Stress Relief Annealed;
The Bauschinger effect.

ABSTRACT

The kind of mild steel, the Bauschinger effect because of strain reversal and strain ageing are indicated to affect significantly the tangent modulus of elasticity. Stub column specimens made from a material that has been pre-stretched in tension have a significantly lower tangent modulus of elasticity than those specimens made from as-received material; the reduction is caused by the Bauschinger effect and a resulting reduction in tangent modulus and yield strength. The reduction happens despite increases in material yield strength due to strain ageing after application of the tensile stretching. This paper has shown great reductions of tangent modulus of elasticity when specimens are made from material pre-stretched in tension compared with as-received specimens. Strain ageing has a great influence in minimizing the tangent modulus of elasticity reductions resulting from prior tensile prestretching. The initial tensile pre-strain of stress-relief-annealed specimens does not affect the tangent modulus of elasticity. No reduction was observed in the tangent modulus of elasticity of specimens prestrained in tension and stress-relief-annealed. The FE analysis according to the ABAQUS code was applied to simulate the stress-strain curves. The numerical and the experimental curves were reasonably similar to each other.

1. Introduction

Curved steel hollow section has the complementary qualities of aesthetic appearance and the sound structural efficiency evident by the streamlined profile and the possession of different major and minor geometric properties, respectively. Tubular components have recently been utilized as structural supports in a wide variety of structures, such as the glass facade supporting members in Terminal 4 of Barajas Airport in Madrid, the glass roof supporting components in International Finance Center

How to cite this article:
Mortazavi, S., Shakiba, M., Zaeimdar, B. (2023). Material Effects on Tangent Modulus of Steel Square Hollow Section. Journal of Rehabilitation in Civil Engineering, 11(2), 01-17. https://doi.org/10.22075/JRCE.2018.1741.1152

in Hong Kong, the society bridge in Braemar, the office building in an airside business park in Ireland and Honda central sculpture in Goodwood [1-6]. Moreover, they have been employed by the gas and oil industries for fluid transfer and well repair [7-10]. Nowadays, the main struggle that structural engineers are dealing with are not only limited to structural behavior but also closely pertained to the architectural perspective [11]. The use of steel hollow sections as structural components in civil engineering applications is gradually growing as a result of increasing awareness amongst architects and engineers about their availability, their addition to the tubular product standard EN 10210 [12] and the release of industry design guidance [13], according to recent studies [14-23, 38]. As you know, during the production process of raw metal material to achieve some basic properties of material, the factory might change the thermal treatment, chemistry and mechanical process. Throughout the fabrication of metal components, the materials experienced some additional processes in comparison to those employed in the fabrication of the parent materials. These processes increase certain material properties, however, decrease other properties. For instance, the process of cold work increases the yield stress of steel although the annealing decreases the yield stress but increase the ductility of steel which was under the cold working process [24, 25]. In service, such steel components can be overloaded and then yielding, under quasi-static loading. If stress reversal occurs thus the properties of material of the component might be altered; rarely these changes may be useful. Sometimes, material suppliers change the member properties by more cold work; For instance, the tensile strength is usually enhanced. It should be noted that engineers commonly believe that the tensile yielding strength is one of the most important properties of material. Under force reversal from tension into the compression force range, the properties of material of component may change noticeably, and allowance must be considered. Under dynamic cyclic force reversal, the material properties could change more significantly than that under static loading, and the structural behavior might be altered significantly. For both dynamic and static conditions, any changes in property of material is crucial and can affect the tangent modulus of elasticity, E_T. The tangent modulus E_T is related to the specimen ultimate load carrying capacity of calculation once repeated loading is conducted during inelastic range. In those conditions, the stress-strain diagram is recorded, despite the discontinuous curve for as-received and annealed mild steel [26]. The concept of tangent modulus thus affects considerably the buckling analysis under these conditions [27].

This study aims to examine the influence of various material properties on E_T values of mild steel specimens. The specimens were cut from Electric Resistance Welded (ERW) tubes. The square tubes are fabricated using cold straightening the flat strip from coils. The flat strip moves through some devices called roll formers and their edges are welded. With more straightening in order to remove the distortion emanating from the process of welding, residual stress are generated as a result of inelastic deformation. Cold straightening procedure of the coil to form a square section result in the steel being strained into the inelastic range; strain ageing will occur depending on the temperature. With regard to the welding process, strain ageing occurs right after welding, as the temperature of the steel increases dramatically. But, additional inelastic straining develops in the last step of straightening operation, and it results in more strain ageing. As the square tube lengths leave the mill, the strain ageing process may be complete. An increase in the yield point may result due to ageing, considering the mild steel type, offsetting the effects of the residual stresses. For example, in comparison to full-killed steel, semi-killed steel is more vulnerable to strain ageing [24, 25]. The residual stresses may be anticipated to reduce the tangent modulus, E_T, as the member is under loading, however, the influences of strain ageing will offset this reduction to some extent. The test results studied herein are stub column compressive tests on the square tubes. The square tube was initially prestrained in tension after manufacture. The prestraining into the inelastic range was selected to be 0.81% or any other inelastic prestrain values. This raised the question as to whether prerstraining should be permitted or not, regardless of the amount of tensile plastic prestraining. The precision is required if the subsequent reduction in the tangent modulus in compression occurs after such prestraining. The tangent modulus of elasticity in compression has been affected, then by the following parameters: (1) strain reversal and the Bauschinger effect (2) amount of inelastic prestrain in tension and (3) strain ageing. Determine the modulus of elasticity using the compressive tests is not easy to obtain with a high accuracy, however compressive tests on stub columns give beneficial data and information about the influence of above-mentioned parameters in the inelastic range. The earlier study of strut compressive tests showed that the above-mentioned parameters affect the performance of the struts.

Afshan et al. [28] presented suitable models to predict the strength increase in cold-formed structural members due to the manufacturing process. Gardner et al. [29] provided basic material properties strain-stress curves for rectangular, square and circular hollow specimens stainless steel. They modified the Ramberg-Osgood method. They provided a relationship between cross-sectional deformation and cross-sectional slenderness capacity. An experimental study of cold-formed and hot-rolled rectangular hollow sections was carried out and the results were compared to each other by Gardner et al. [30]. They showed that increases in ultimate and yield strength beyond those quoted in the respective mill certificate were observed in the corner regions of the cold-formed sections. These are because of the cold-working of the rectangular hollow sections during production. Hu et al. [31] determined the behaviour of thick-wall cold-rolled steel sections with rectangular and square hollow cross-sections. Cold forming process effects on material properties were studied. The average design strength determined using the average design yield stress of the full section was the same as the predicted based upon material properties that resulted from the normal flat coupon tests. Rossi and Degee [32] reported that the process of cold-forming enhanced the material properties of the steel by strain hardening and consequently increased the yield and ultimate strength compared to nominal material properties. Using the virgin sheet material properties, the mechanical properties of cold-formed stainless steel profiles were determined after the cold working process of fabrication by a new formula. Daboon et al. [33] studied an experimental study between unstiffened and stiffened stainless steel tubular stub columns under compression. They resulted that the design relationships specified in ASCE and European standards overestimate the column strengths of rectangular and square hollow sections built by welding and cold-forming. Young and Lui [34] carried out tests on high strength cold-formed stainless steel members under compression. It has resulted that the predicted design strengths by the code of practice were conservative. Xiao and Zhao [35] discussed the circular tube's capacity of very high strength under compressive load. The tensile yield strength, modulus of elasticity and ultimate tensile strength were determined. It was found that the local buckling limits in most design codes of practice are conservative when applied to Very High Strength tubed (VHS). Jandera and Machacek [26] studied the effect of residual stresses induced in stainless steel. The material property and behavior of members under compressive load are discussed. The cross-section of the member was a square hollow section as well. The effect of residual stress on the stress-strain curves regarding initial modulus of elasticity and non-linearity was discussed by comparison of stress-relief-annealed and as-received materials. It was shown that the effect of residual stresses may increase load-carrying capacity. In this paper, to study the material effect on tangent modulus of steel square hollow section, experiments of the thin-walled square hollow section stub columns fabricated by mild steel were carried out. Finite element analysis based on ABAQUS code was applied to study and predict the stress-strain curves of the stub column tests.

2. Testing program

The employed material was anticipated to be influenced by the strain ageing process, being rimmed steel. From this material a 63.5 mm width × 2.6 mm square hollow section tube was used for testing. Being in the as-received condition the ERW square hollow tube could be fully aged with respect to the plastic strains. The next plastic straining, included in the testing by tensile pre-strain (0.81%), would initiate further strain ageing. Specimens could be aged at ambient temperature, but in this research full ageing was accelerated by placing the specimens in an oven for 2 hours at 100 (^{0}C) after prestraining. Tensile tests was conducted on as-received samples cut from the hollow steel tubes resulted in yielding stress (0.2% offset) equal to 332 MPa, and ultimate tensile strength of 381MPa. The value of ultimate stress divided by yield stress was 1.14. Thus, the strength increase as a result of strain hardening of steel was trivial. The length of test specimens were equal to 275 mm. The specimens were short enough to prevent any possibility of overall instability influencing results (length 3 times the diameter) [36]. The ends of the stub columns were carefully squared and ground before testing. One end of the stub column specimens was fixed and the other end was under compressive load by a displacement method. A stub column specimen was placed into a testing machine and the compressive load was directly applied to the stub column specimen. The strain rate was kept constant at 0.005 mm/sec for all the tests. A pair of linear variable displacement transducers (LVDT) was used to measure the axial shortening deformation between the two ends. Table 1 presents a summary of these test specimens. As indicated in Table 1, and in order to see the real behavior of each specimen, the number of three specimens manufactured for each case and all those specimens were subjected to their loading conditions.

Table 1. Specimen Treatments.

Test Type and Spec. No. (C-compression, T-tension)	State of Square Tube	Heat Treatment	Strain Ageing	No. of Tests
T (T1, T2, and T3)	As-Received	Nil	Nil	3
C1 (C11, C12, and C13)	As-Received	Nil	Nil	3
C2 (C21, C22, and C23)	As-Received	SRA[a]	Nil	3
C3 (C31, C32, and C33)	0.81%[b]	SRA[a]	Nil	3
C4 (C41, C42, and C43)	0.81%[b]	Nil	Full[c]	3
C5 (C51, C52, and C53)	0.81%[b]	Nil	Nil	3

[a] SRA Stress-Relief-Annealed (30 minutes at 620 ^{o}C).

[b] tensile prestrain value in percent before stated heat treatment.

[c] two hours at 100 ^{o}C.

2.1. Test Results

In all tests of the stub columns a same testing machine was utilized in a displacement controlled condition. The loading rate of deformation was constant at 0.005 mm/sec for the stub column tests (Fig.1.). Some references were necessary by which the different behavior of tested stub column, due to the various parameters and effects, can be examined. Therefore, tests on stress-relief annealed (SRA) and as-received square tube were carried out. The temperature of stress-relief-annealing for the specimens was 620 (^{o}C) for 30 minutes. This process was used to relieve the residual stresses induced during the manufacturing process of square hollow section. Fig.2 illustrates a typical test result on the as-received square tube under tension and Fig.3 indicates a test result on as-received square tube under compression.

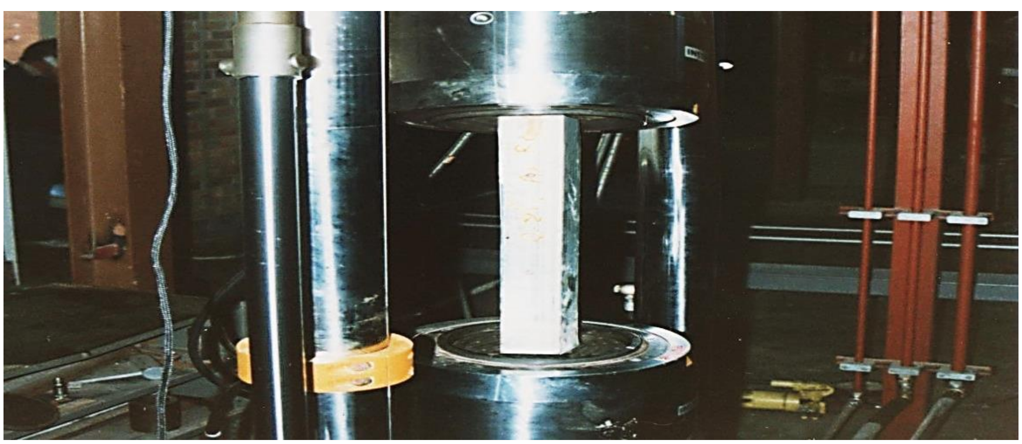


Fig. 1. Stub Column Test Setup.

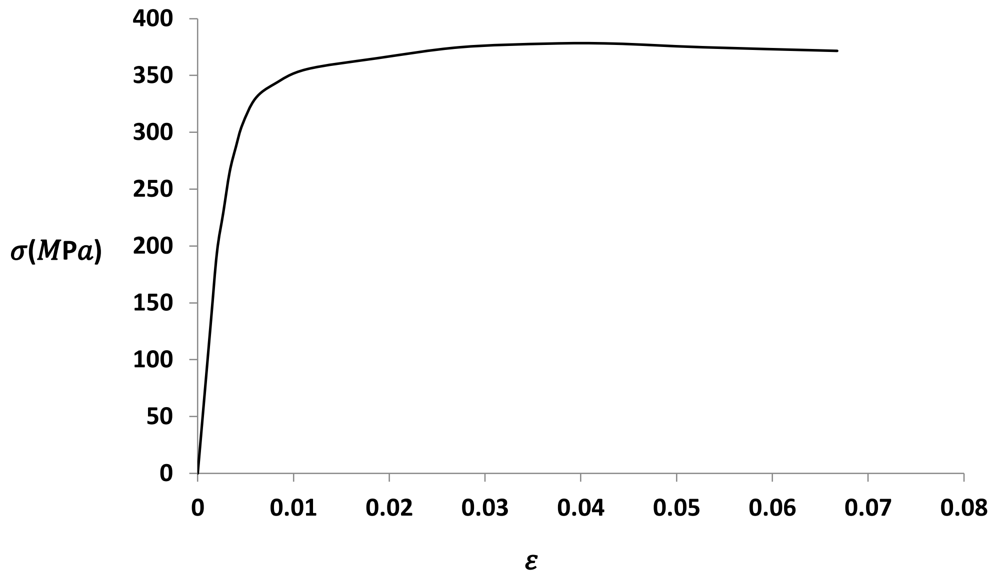


Fig. 2. Tensile Stress-Strain Curve for As-Received Square Tube (T3).

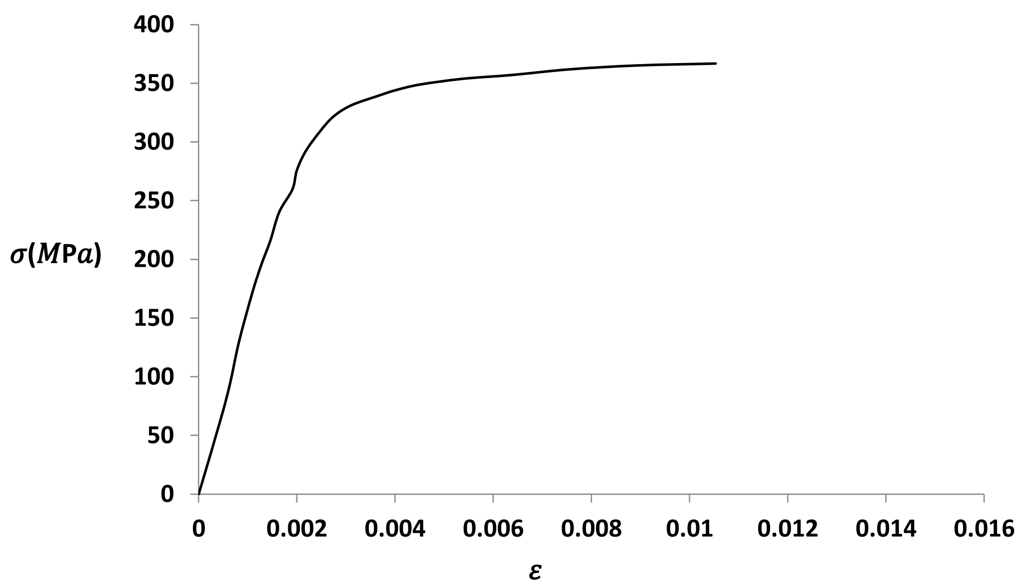


Fig. 3. Compressive Stress-Strain Curve for As-Received Square Tube (C11).

The influence of stress-relief annealing (30 minutes at 620˚C), resulted in the compressive test curves shown in Fig.4 for 0.81% SRA (initially 0.81%prestrained in tension and then stress-relief-annealed) and as-received SRA. No effect can be seen on the stress-strain curves due to initial tensile prestrain for stress-relief-annealed specimens.

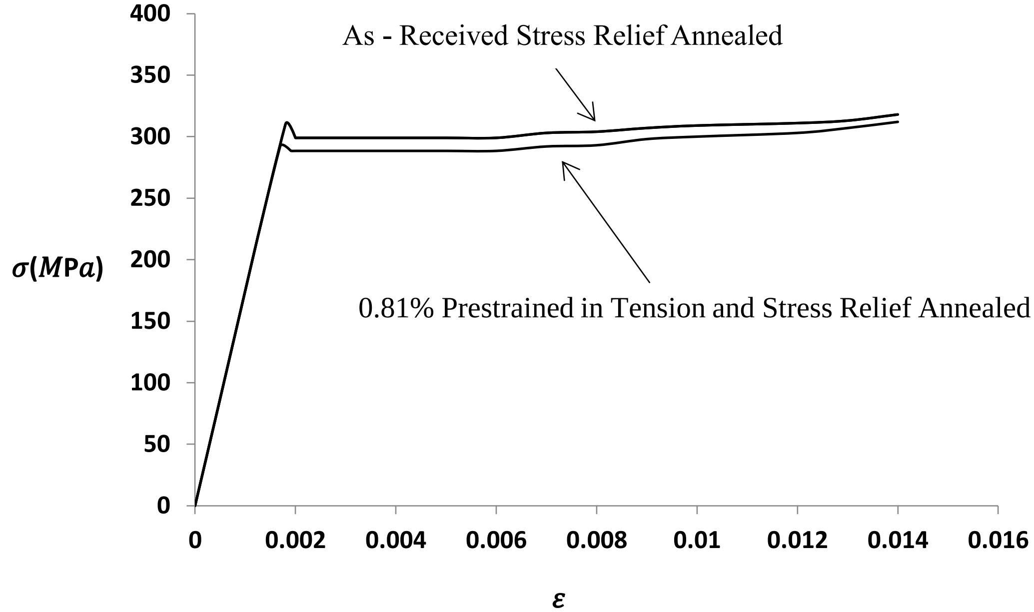


Fig. 4. Compressive Stress-Strain Curves for As-Received SRA and 0.81% SRA.

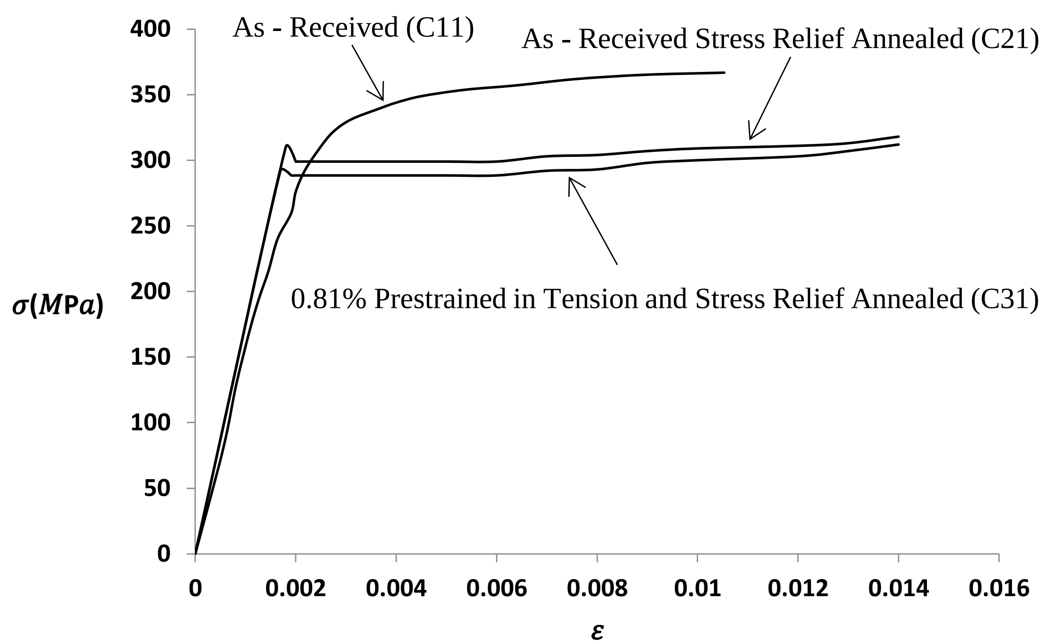


Fig. 5. Compressive Stress-Strain Curves for As-Received, As-Received SRA and 0.81% SRA.

The stress-strain curve of as-received compared to the as-received SRA and 0.81% SRA curves (Fig.5.), the yield plateau of the SRA stub column tests was well defined, indicating that residual stresses of the square section existed. The process of stress-relief-annealing reduced the yield stress of specimens, although the stub column specimens were free of residual stresses created during the manufacturing. Fig.6 indicates the compressive test results on specimens subject to 0.81% of prestrain in tension with ageing together with no ageing treatment. Ageing treatment was accomplished by placing the specimens in an oven for two hours at 100°C after prestraining in tension by 0.81%. The influence of full ageing versus no ageing for a prestrain of 0.81% is obvious in Fig.6. The compressive stress-strain curves of specimens are illustrated in Fig.7 for as received specimen, 0.81% prestrained in tension without an ageing specimen and 0.81% prestrained and fully aged specimen. It can be seen in Figs.6 and 7, the Bauschinger effect (the reduction of modulus of elasticity and yield stress) is more critical for specimens with no ageing treatment after prestraining in tension. It must be mentioned that in the testing program for each test category, there were three specimens which after investigating their results, had similar behavior observed.

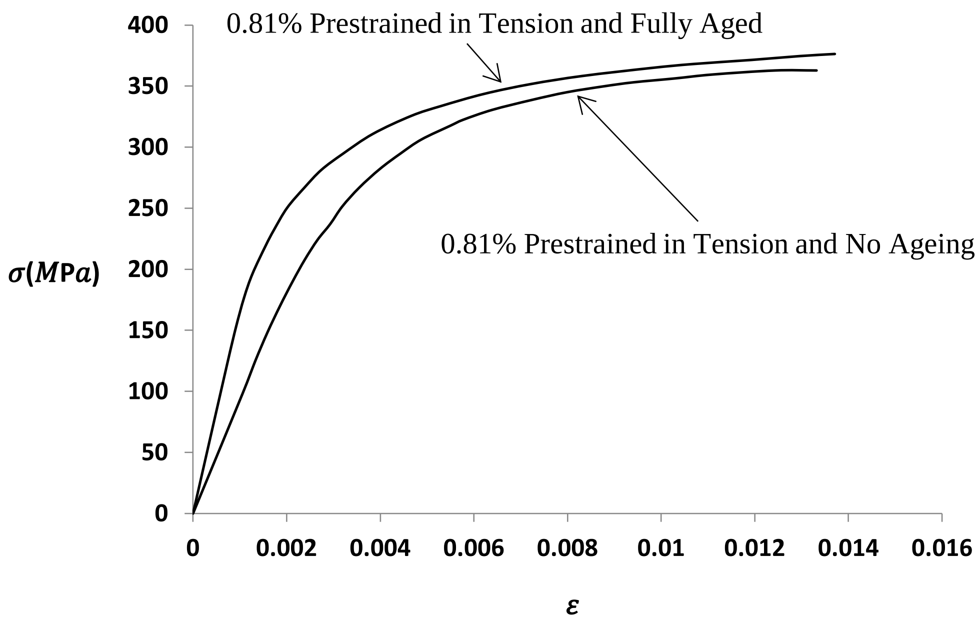


Fig. 6. Compressive Stress Strain Curves for 0.81% No Ageing and 0.81% Full Ageing.

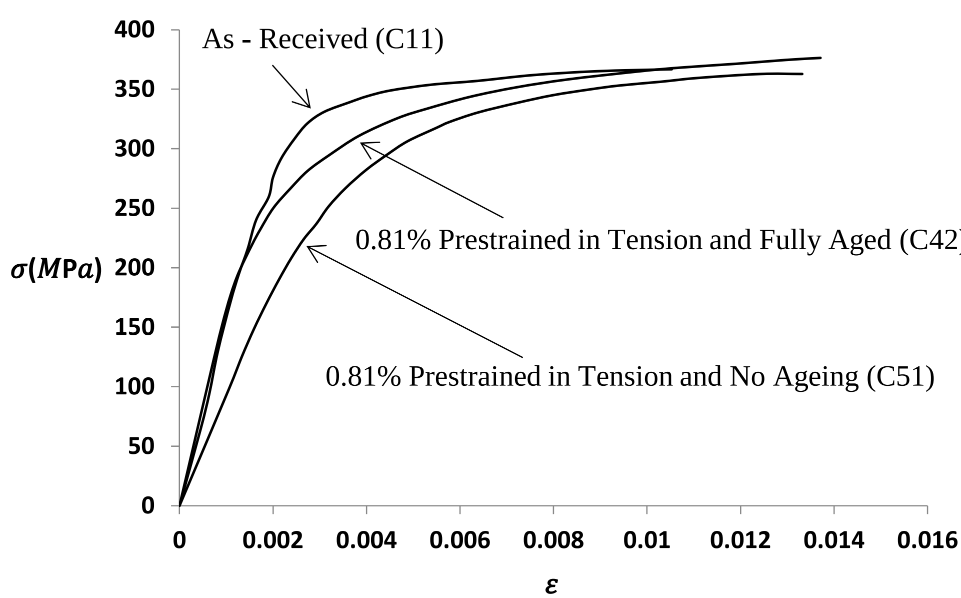


Fig. 7. Compressive Stress Strain Curves for As-Received, 0.81% No Ageing and 0.81% Full Ageing.

3. Numerical Model

3.1. Finite element analysis

The finite element program ABAQUS version 6.13 [37] was used in the present work to create a finite element model for specimens. The shell elements were four-node shells with reduced integration (S4R) to model the stub column specimens. Mesh convergence studies were managed to optimize finite element mesh that provides relatively accurate results with low computational time. The Poisson's ratio was taken 0.3 for steel.

In the numerical models, one end of the specimens was fixed and the other end of the specimens were under compression load using a displacement method. To obtain the whole load-displacement curves with the descending parts, an incremental iteration method was used. A specimen was placed into a testing machine and the compressive load was applied to the specimen. In the finite element model, the load has been applied in ten steps that the top surface has been brought down 0.289575 mm in each level. The top and bottom surfaces of the stub column specimens have been fixed; namely, no degrees of freedom except for the vertical displacement at both ends. To simulate the stress-strain curves of the stub column specimens, both geometric and material non-linearities were included in the numerical models. The stress-strain curves (material properties) were modelled by the multi-linear isotropic hardening model. Fig.8 shows the stress distribution of as-received stub column specimens under compressive load and the stress contour (Von Mises yield criteria) also illustrates the failure modes of the as-received specimen through the finite element model. The deformed shape of the as-received stub column under compressive load is presented in Fig.9. The comparison of the typical stress-strain curves between experimental results and finite element analysis on stub column specimens under compressive load are shown in Figs.10-14. The numerical results can accurately predict the experimental results. The comparison also indicated that the finite element model was reliable in the prediction of the stress-strain behavior of the stub column specimens and also showed its capability to simulate the behavior of the stress-strain curves of the stub columns with good accuracy.

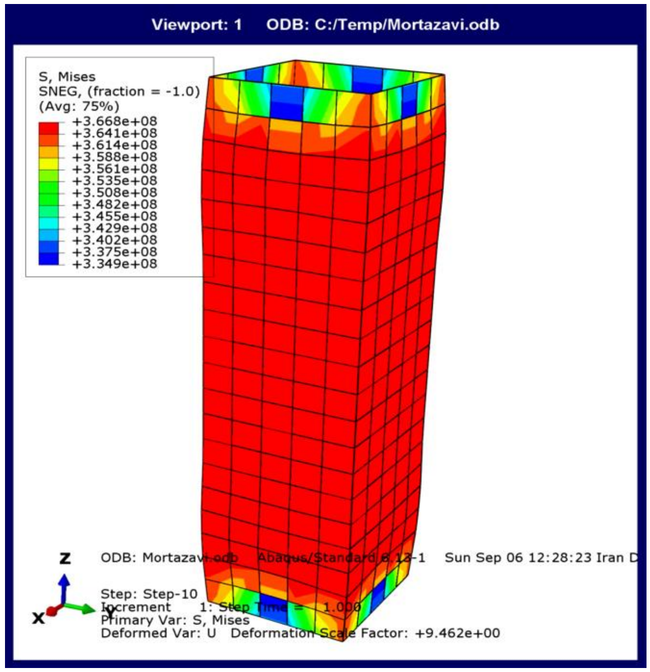


Fig.8. Stress Contour of As-Received Specimen.

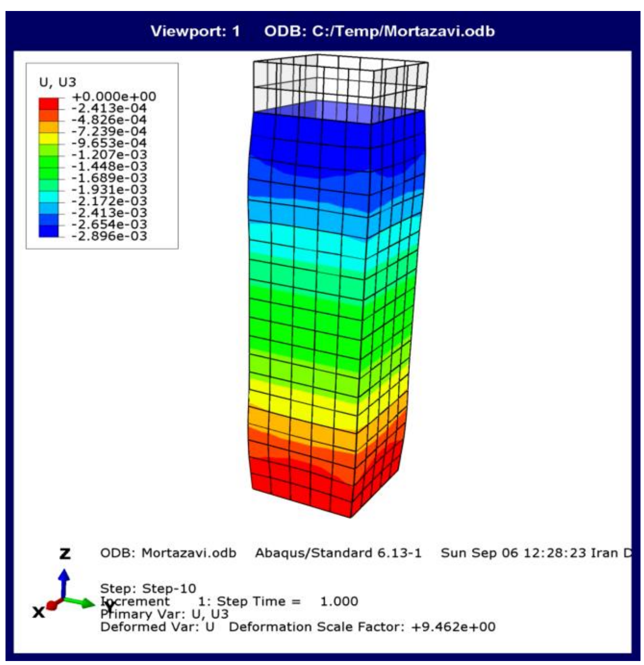


Fig.9. Deformed Shape of As-Received Specimen.

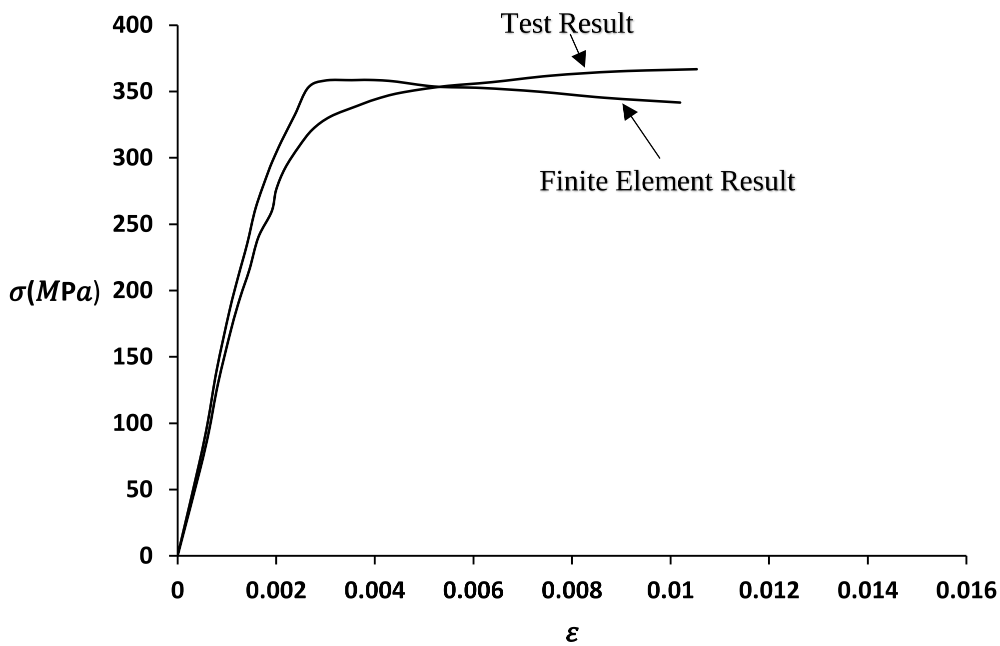


Fig.10. Comparison Between Tested and FE Model Stress-Strain Curves for As-Received Square Tube.

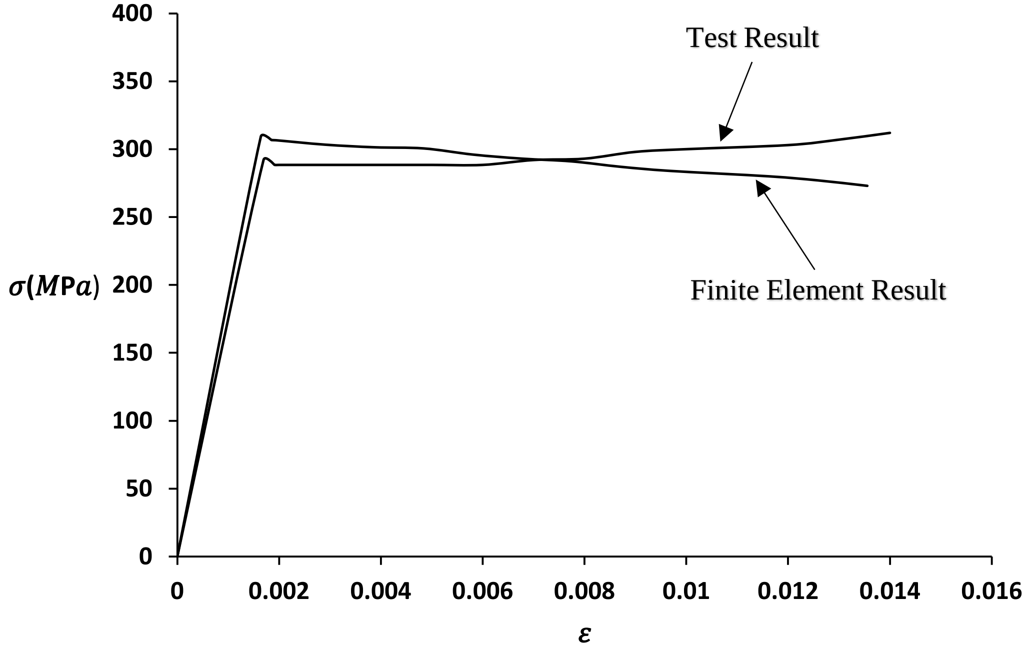


Fig.11. Comparison Between Tested and FE Model Stress-Strain Curves for 0.81% Prestrained in Tension and SRA Square Tube.

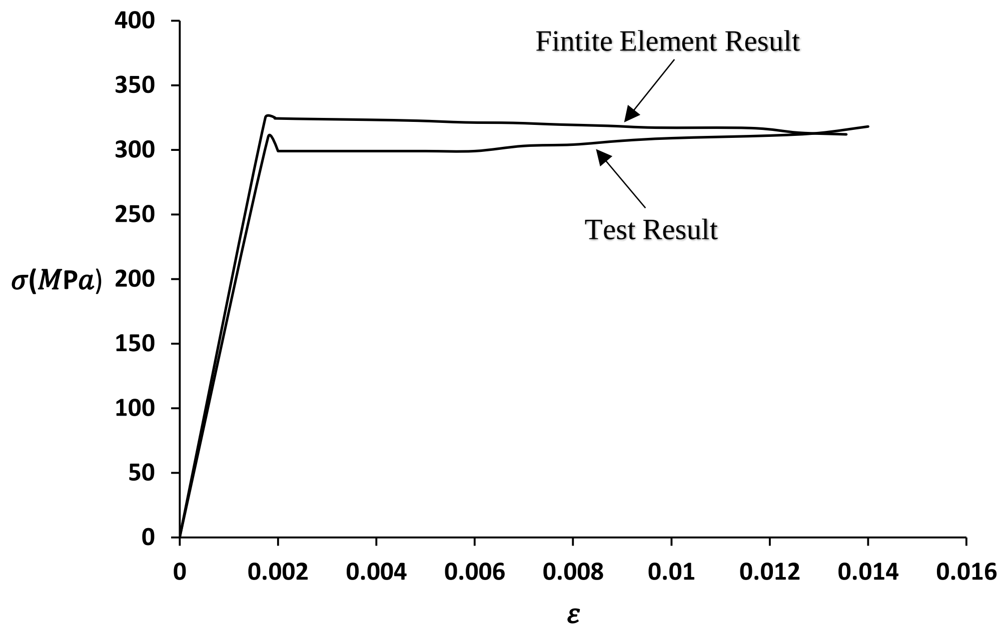


Fig.12. Comparison Between Tested and FE Model Stress-Strain Curves for As-Received SRA Square Tube.

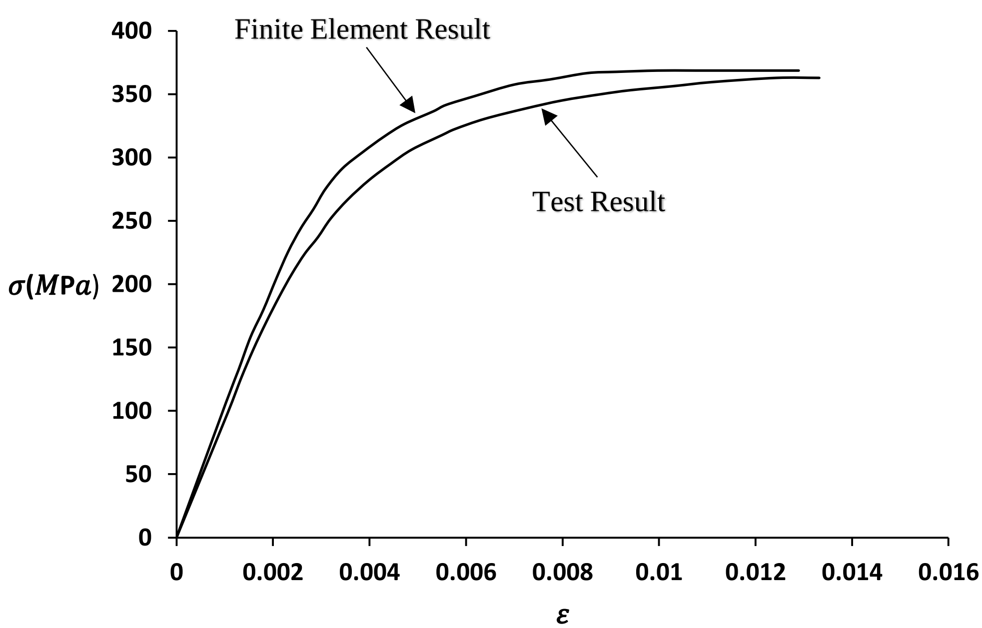


Fig.13. Comparison Between Tested and FE Model Stress-Strain Curves for 0.81% Prestrained in Tension and No Ageing Square Tube.

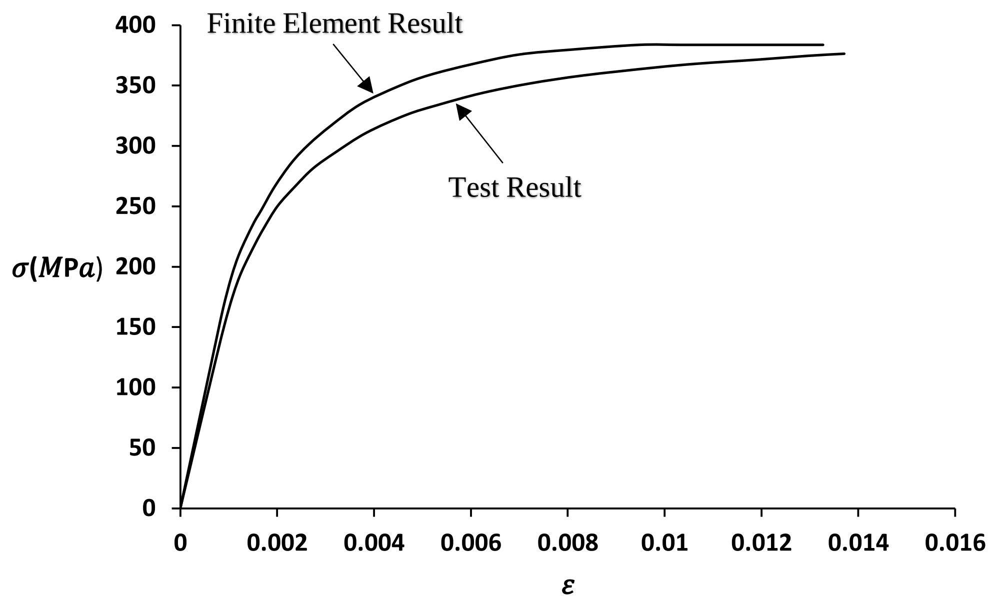


Fig.14. Comparison Between Tested and FE Model Stress-Strain Curves for 0.81% Prestrained in Tension and Fully Aged Square Tube.

4. Tangent Modulus Values, E_T

From the stress-strain diagrams shown in Figs.3, 4 and 6, tangent modulus, E_T, was computed graphically versus the values related to the axial compressive stress, σ. Figs.15 and 16 show the results for modulus of elasticity versus stress from the stress-strain curves of the type given in Figs.3, 4 and 6. While the computation of the slope values of stress-strain diagrams, for calculating the modulus of elasticity of specimens, may not be very accurate, the effects of the mentioned parameters could be easily observed. The variation of tangent modulus with respect to stress was not significantly different for the stress-relief-annealed conditions (as-received SRA and 0.81% SRA) as presented in Fig.15. However, the curves presented in Fig.16 indicateds that a significant variation between test results from one test to another is observed (as-received, 0.81% with no ageing and 0.81% with ageing). By considering each case, a comparative result can be induced. The value of modulus of elasticity in the inelastic range and the effect of the parameters has previously been stated.

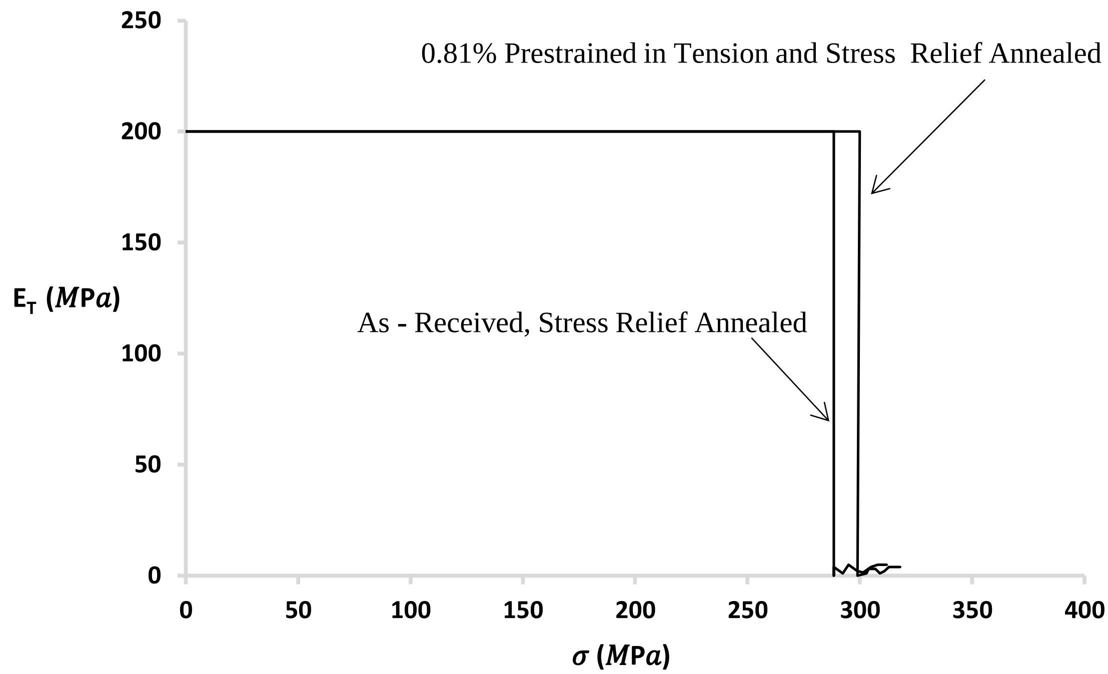


Fig.15. Modulus of Elasticity E_T vs Stress σ, As-Received SRA and 0.81% SRA.

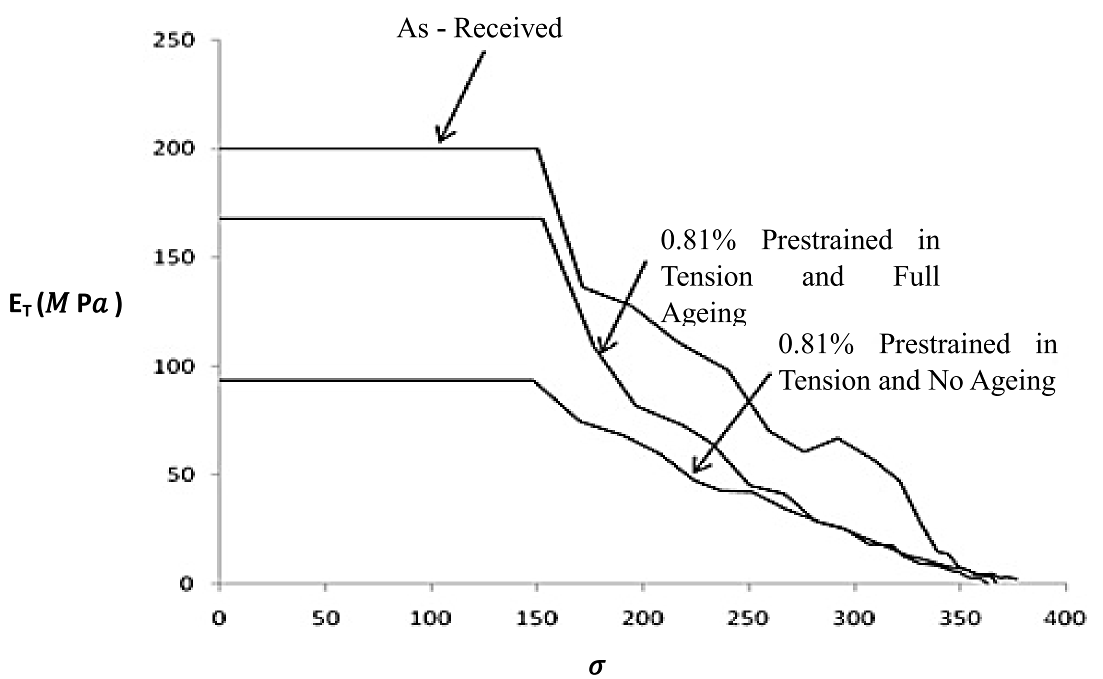


Fig.16. Modulus of Elasticity E_T vs Stress σ, As-Received, 0.81% No Ageing and 0.81% Fully Age.

5. Conclusions

To compare the stress-strain curve of the as-received stress-relief-annealed (SRA), 0.81% prestrained in tension and SRA stub column specimens, the very well-defined yield plateau of the SRA stub column tests showed that the residual stresses existed during the manufacturing process of the square hollow section. The stress-relief-annealing process reduced the yield stress of stub columns. From the results obtained from this study, it was revealed that no significant variation in stress-strain curves for stress-relief-annealed is observed due to initial plastic prestraining in tension. Also, the modulus of elasticity (E_T) of the stress-relief-annealed (SRA) curve is almost the same as the 0.81% pre-strain in tension and stress-relief-annealed curve (0.81% SRA). The as-received curve had the highest value for E_T, whereas the 0.81% prestrained in tension with no ageing curve had the lowest value. The 0.81% prestrained curve is quite well below that for the as-received with no prestraining curve. This outcome shows that the Bauschinger influence is remarkable regarding initial plastic tensile prestraining. Ageing has a noticable effect on the tangent modulus of elasticity. The 0.81% prestrained in tension and a fully aged diagram is quite above that for the 0.81% prestrained in tension without an ageing curve in the same range of stress. Finite element analysis using the ABAQUS was carried out to predict the stress-strain curves of the stub column specimens. Regarding the results presented, it can be concluded that, for the rimmed steel, with low strain hardening:

1. The initial plastic tensile prestraining reduces the value of tangent modulus of elasticity E_T.
2. The effect on strain ageing is completely notable; full ageing increases the values of E_T, for a given value of plastic tensile pre-strain.
3. Engineers must understand the significance of knowing the history of the prior strain of existing material, as some of the material suppliers conduct extra tensile straining to improve the yielding point in tension; Hence, the modulus in compression could reduce significantly.
4. For ultimate load capacity computation of struts, allowance should be made because of the reduced values for E_T under force reversal.
5. The initial tensile pre-strain of stress-relief- annealed square hollow section has no effect on the modulus of elasticity.
6. By comparing the numerical results with the experimental results of the stub columns, it was found that the numerical model could predict the experimental stress-strain curves with high accuracy.
7. Modulus of elasticity is a very important parameter to design steel columns. The reduction in the modulus of elasticity results reduction in the load capacity of compression members. Regarding the work presented in the paper, the modulus of elasticity depends on the type of materials that may be used (as-received, prestrained with no aging, prestrained then fully aged, stress-relief-annealed).

Credit authorship contribution statement

S.M.R Mortazavi: Project administration, Supervision, Writing-original draft, Validation, Conceptualization, Methodology. **Milad Shakiba:**

Investigation, Resources, Writing-review &editing, Conceptualization, Formal analysis, Validation, Methodology. **Behrouz Zaeimdar:** Investigation, Formal analysis, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] L. Gardner and T. M. Chan, “Cross-section classification of elliptical hollow sections,” Steel Compos. Struct., vol. 7, no. 3, p. 185, 2007.

[2] T. M. Chan and L. Gardner, “Compressive resistance of hot-rolled elliptical hollow sections,” Eng. Struct., vol. 30, no. 2, pp. 522–532, 2008.

[3] T. M. Chan and L. Gardner, “Bending strength of hot-rolled elliptical hollow sections,” J. Constr. Steel Res., vol. 64, no. 9, pp. 971–986, 2008.

[4] T. M. Chan and L. Gardner, “Flexural buckling of elliptical hollow section columns,” J. Struct. Eng., vol. 135, no. 5, pp. 546–557, 2009.

[5] T. M. Chan, L. Gardner, and K. H. Law, “Structural design of elliptical hollow sections: A review,” Proc. Inst. Civ. Eng. Struct. Build., vol. 163, no. 6, pp. 391–402, 2010, doi: 10.1680/stbu.2010.163.6.391.

[6] L. Gardner, T. M. Chan, and M. A. Wadee, “Shear response of elliptical hollow sections,” Proc. Inst. Civ. Eng. Build., vol. 161, no. 6, pp. 301–309, 2008.

[7] A. Karrech and A. Seibi, “Analytical model for the expansion of tubes under tension,” J. Mater. Process. Technol., vol. 210, no. 2, pp. 356–362, 2010.

[8] T. Pervez, A. C. Seibi, and A. Karrech, “Simulation of solid tubular expansion in well drilling using finite element method,” Pet. Sci. Technol., vol. 23, no. 7–8, pp. 775–794, 2005.

[9] P. Barnes, R. Hejazi, and A. Karrech, “Instability of mechanically lined pipelines under large deformation,” Finite Elem. Anal. Des., vol. 146, pp. 62–69, 2018.

[10] C. Guo, M. Elchalakani, A. Karrech, M. R. Bambach, and B. Yang, “Behaviour and design of cold-formed CHS under static pure bending through finite element analysis,” Thin-Walled Struct., vol. 147, p. 106547, 2020.

[11] M.-T. Chen and B. Young, “Cross-sectional behavior of cold-formed steel semi-oval hollow sections,” Eng. Struct., vol. 177, pp. 318–330, 2018.

[12] B. S. EN10210, “2. British Standard: Hot finished structural hollow sections of non-alloy and fine grain steels Part 2: Tolerances, dimensions and sectional properties,” Br. Stand. Inst., 2006.

[13] S. (Steel C. I. and B. C. S. Association), “Steel building design: Design data in accordance with Eurocodes and the UK national annexes.” SCI London, 2009.

[14] T. Haque, J. A. Packer, and X.-L. Zhao, “Equivalent RHS approach for the design of EHS in axial compression or bending,” Adv. Struct. Eng., vol. 15, no. 1, pp. 107–120, 2012.

[15] A. Insausti and L. Gardner, “Analytical modelling of plastic collapse in compressed elliptical hollow sections,” J. Constr. Steel Res., vol. 67, no. 4, pp. 678–689, 2011.

[16] K. H. Law and L. Gardner, “Lateral instability of elliptical hollow section beams,” Eng. Struct., vol. 37, pp. 152–166, 2012.

[17] K. H. Law and L. Gardner, “Buckling of elliptical hollow section members under combined compression and uniaxial bending,” J. Constr. Steel Res., vol. 86, pp. 1–16, 2013.

[18] M. Theofanous, T. M. Chan, and L. Gardner, “Structural response of stainless steel oval hollow section compression members,” Eng. Struct., vol. 31, no. 4, pp. 922–934, 2009.

[19] M. Theofanous, T. M. Chan, and L. Gardner, “Flexural behaviour of stainless steel oval hollow sections,” Thin-Walled Struct., vol. 47, no. 6–7, pp. 776–787, 2009, doi: 10.1016/j.tws.2009.01.001.

[20] M.-T. Chen and B. Young, “Material properties and structural behavior of cold-formed steel elliptical hollow section stub columns,” Thin-Walled Struct., vol. 134, pp. 111–126, 2019.

[21] M. T. Chen and B. Young, “Tests of cold-formed steel elliptical hollow section beams,” 2016.

[22] M.-T. Chen and B. Young, “Structural performance of cold-formed steel elliptical hollow section pin-ended columns,” Thin-Walled Struct., vol. 136, pp. 267–279, 2019.

[23] P. Kumar, S. Pandey, and P. R. Maiti, “A Modified Genetic Algorithm in C++ for Optimization of Steel Truss Structures,” J. Soft Comput. Civ. Eng., vol. 5, no. 1, pp. 95–108, 2021.

[24] R. Abbaschian and R. E. Reed-Hill, Physical Metallurgy Principles-SI Version. Cengage Learning, 2009.

[25] H. M. Tensi, A. Stich, and G. E. Totten, “Quenching and quenching technology,” Chapter, vol. 4, pp. 157–249, 1997.

[26] M. Jandera, L. Gardner, and J. Machacek, “Residual stresses in cold-rolled stainless steel hollow sections,” J. Constr. Steel Res., vol. 64, no. 11, pp. 1255–1263, 2008.

[27] G. Charles, “Salmon, John E. Johnson and Faris A. Malhas-" Steel Structures-Design and Behavior".” Prentice Hall, 2008.

[28] S. Afshan, B. Rossi, and L. Gardner, “Strength enhancements in cold-formed structural sections—Part I: Material testing,” J. Constr. Steel Res., vol. 83, pp. 177–188, 2013.

[29] L. Gardner and D. A. Nethercot, “Experiments on stainless steel hollow sections—Part 1: Material and cross-sectional behaviour,” J. Constr. Steel Res., vol. 60, no. 9, pp. 1291–1318, 2004.

[30] L. Gardner, N. Saari, and F. Wang, “Comparative experimental study of hot-rolled and cold-formed rectangular hollow sections,” Thin-walled Struct., vol. 48, no. 7, pp. 495–507, 2010.

[31] S.-D. Hu, B. Ye, and L.-X. Li, “Materials properties of thick-wall cold-rolled welded tube with a rectangular or square hollow section,” Constr. Build. Mater., vol. 25, no. 5, pp. 2683–2689, 2011.

[32] B. Rossi, H. Degée, and F. Pascon, “Enhanced mechanical properties after cold process of fabrication of non-linear metallic profiles,” Thin-walled Struct., vol. 47, no. 12, pp. 1575–1589, 2009.

[33] M. A. Dabaon, M. H. El-Boghdadi, and M. F. Hassanein, “A comparative experimental study between stiffened and unstiffened stainless steel hollow tubular stub columns,” Thin-walled Struct., vol. 47, no. 1, pp. 73–81, 2009.

[34] B. Young and W.-M. Lui, “Tests of cold-formed high strength stainless steel compression members,” Thin-Walled Struct., vol. 44, no. 2, pp. 224–234, 2006.

[35] X.-L. Zhao, “Section capacity of very high strength (VHS) circular tubes under compression,” Thin-Walled Struct., vol. 37, no. 3, pp. 223–240, 2000.

[36] A. A. S. for T. and Materials, Standard test methods for tension testing of metallic materials. ASTM international, 2009.

[37] HKS, “ABAQUS/Standard user’s manual.” ABAQUS Inc. Pawtucket, RI, 2005.

[38] Shekarchi M, Yekrangnia M, Biniaz A, Raftery GM. Effect of elevated temperatures on the compressive behavior of timber filled steel and pultruded GFRP tubes. Compos Struct. 2021;271:114135.