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The Assessment of Elastic Follow-up Effects on Cyclic Accumulation of inelastic Strain under Displacement Control Loading

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Abstract: Assessment of strain accumulation due to nonlinear events like creep, plasticity or ratcheting phenomenon has gained importance, as it causes an increase in creep and fatigue damage in structures. Some factors such as the magnitude of loading, constitutive equations or the elastic regions around the nonlinear events have an effect on the rate of strain accumulation. The elastic follow-up can explain the mechanism of plastic strain accumulation. This phenomenon may occur when a mechanical structure with elastic manner is connected to non-linear events. In cyclic loading with non-zero mean stress, the plastic strain may be accumulated. This behavior is known as ratcheting and usually takes place under cyclic load-control conditions. A new simplified method is proposed in this paper in order to assess the effects of elastic follow-up on the ratcheting behavior of two-plate model made up of AISI 1045 steel under displacement-control loading and a set of experimental tests are conducted to verify this method. The tests were carried out by a servo-hydraulic Zwick-Roell machine. The test results confirm the accuracy of the proposed method and also reveal that in the presence of EFU in the system, the cyclic accumulation of plastic strain in addition to the load-control conditions may occur locally in the displacement-control conditions.

Keywords: Elastic follow-up; Ratcheting Strain; Assessment; Cyclic loading; Displacement Controlled condition; Load Controlled condition; Stiffness

1. Introduction

Strain accumulation in mechanical structures has gained importance since it causes an increase in creep and fatigue damage of materials. When a mechanical structure with elastic manner is connected to non-linear events and they are subjected to a displacement-control loading, the plastic strain may be accumulated. Some of these non-linear events that can be noted are structural discontinuities, local creep, ratcheting strain and so on. The elastic follow-up

(EFU) concept can explain the plastic strain accumulation. In these cases, the high rigidity portion of elastic region of mechanical structures may enhance the force to the regions with low rigidity.

The EFU was first raised by Robinson (1939) in work focused on assessing the impact of creep damage on un-cracked structures. He tested the relaxation of bolted joints due to creep and noted that the amount of initial elastic deformation in the bolt and flange was important in determining the rate of relaxation due to creep in the bolt. Robinson accidently referred this phenomenon as follow-up elasticity to refer to the amount of elastic deformation in the flange; but he did not present a definition for this phenomenon. He described that when the flange is rigid the EFU is zero and the plastic strain is accumulated in the bolt because of the creep. In this situation if the ends of the bolt remain fixed, the force in the bolt reduces. In other words, when the flange is elastic, EFU is nonzero, and as creep occurs in the bolt, the ends of the bolt move apart as a result of elastic recovery of a flange. Therefore, the relaxation of force in the bolt is decreased compared to the case of the rigid flange. As EFU increases in the joints, the rate of relaxation of force decreases. Robinson (1955) also examined creep relaxation in several piping expansion loops and demonstrated that, creep strain accumulation could occur in deformation-control loading conditions. Following on from Robinson's early work, a uni-axial description of EFU due to creep has been provided by many authors. Boyle et al. (1981) and Kasahara (2001) presented a simple description for quantifying EFU in a simple two-bar in series model subjected to a fixed displacement and the creep power law. At elevated temperatures, EFU becomes more important (Boyle et al. 1987). A number of researchers including Teramae (1983), Dhalla (1986) and Roche (1986) investigated the influence of EFU on creep in high temperature pipe work systems.

The stress is usually classified as primary and secondary parts. In principle, primary stress is necessary to satisfy equilibrium equations and cannot disappear as a result of non-elastic deformations. Secondary stress is necessary to satisfy compatibility equations (material continuity) and may disappear due to non-elastic deformations (plasticity or creep), (Roche 1988). A number of researchers have proved that when EFU exists in mechanical components, the secondary stresses must be classified as primary either partly or fully depending on the level of associated elastic follow-up (Dhalla 1991). Although residual stresses are classified as secondary, it has come to the attention of many researchers that it may be necessary to treat these stresses as primary when the associated EFU in mechanical system is high (Hadidi-Moud et al. 2008 and Arid et al. 2008). Recent studies were carried out by Fujioka (2013), Ainsworth (2012) and Boyle (2013) which investigated the impact of EFU on creep and provided guidelines for fast reactor structural design standards, and fitness-for-service codes.

Many components may be operated under cyclic loading conditions. In the case of cyclic loading with non-zero mean stress, the cyclic accumulation of plastic strain which is known as ratcheting may occur (Ohno 1997). This behavior usually takes place under cyclic load-control conditions and accelerates damage accumulation and reduces fatigue life of mechanical components (Chen et al. 2005). The main parameters which have effects on ratcheting behavior are cyclic loading conditions (stress amplitude and mean stress), and viscosity of the materials (Chen et al. 2006). Ratcheting had been extensively studied in the past three decades. Jain et al. (1978) investigated the impacts of mode of buckling and shape of cross section on the hysteresis behavior of steel tube under cycling axial loading. Chen et al. (2009) investigated the effects of stress amplitude, mean stress, loading history and rate of stress on the ratcheting behavior of high-nitrogen steel X13CrMnMoN18-14-3 under uniaxial loading. Shariati et al. (2012) and Shariati et al. (2014) carried out an experimental study to investigate the softening and ratcheting behaviors of SS316L cantilevered cylindrical shells under cyclic bending load. The cyclic plasticity models were also proposed by researchers including Chaboche et al. (1990), Ohno (1998) and AbdelKarim et al. (2000). A detailed reviews of some unified viscoplastic constitutive theories and various plasticity rule which used for modeling the ratcheting behavior of materials can be found in chaboche (2008). Halama et al. (2016) studied the influence of mean stress and stress amplitude on steady state ratcheting of ST52 steel and presented a new cyclic plasticity model based on the AbdelKarim–Ohno model.

As ratcheting is a non-linear event, EFU may have some influence on this phenomenon. Taleb et al. (1998) investigated the effect of elastic follow-up on ratcheting behavior of metallic structures. They concluded that the presence of EFU in a system has influenced the ratcheting behavior of the system. Also Taleb (1998) examined the behavior of Bitube models by the simplified methods and confirmed that the elastic analysis cannot be always considered to be reliable because it is not able to take into account the effect of the elastic follow-up phenomenon. In this paper the effect of EFU on the cyclic accumulation of plastic strain or ratcheting behavior of two-plates in series under displacement-control loading conditions are investigated by using the proposed simplified method and the experimental tests. a uni-axial test has been considered in order to compare the results with experimental results. The tests were carried out by a servo-hydraulic Zwick-Roell machine. The results reveal that in the presence of EFU in mechanical structures, the cyclic accumulation of plastic strain or ratcheting may occur locally in displacement-control loading conditions in addition to the load-control loading conditions.

2. Elastic Follow-up and ratcheting behavior

As mentioned above, many researchers have explained the concept of elastic follow-up. For elastic follow up to occur, there should be a non-linear event in a mechanical structure with elastic manner. In other word, it is essential that the system be loaded non-elastically (plasticity, local creep or cyclic plastic strain).

The definition of EFU factor for relaxation behavior which is proposed by the R5 (2003) assessment procedure for the high temperature response of structures is applied in this study. This definition is illustrated in Fig. 1. The EFU factor, Z, is defined as:

$$\frac{d\bar{\varepsilon}_c}{dt} + \frac{Z}{\bar{E}}\frac{d\bar{\sigma}}{dt} = 0 \tag{1}$$

where:

$\bar{\sigma}$ is the equivalent normal stress, $\bar{\varepsilon}_c$ is the equivalent creep strain, $\bar{E}$ is the equivalent elastic modulus and t is the creep time.

Fig. l: Graphical illustration of the definition of elastic follow-up factor in R5 (2003).

In Fig. 1, σ_A and σ_B are the stresses before and after the relaxation, respectively at peak stress of the system which is defined as initial and final state of stress relaxation in this paper. In R5 (2003), it is shown that the EFU factor may be estimated from:

$$Z = \frac{\Delta\bar{\varepsilon}_{inc} + \Delta\bar{\sigma}'/\bar{E}}{\Delta\bar{\sigma}'/\bar{E}} = \frac{\Delta\bar{\varepsilon}_c}{\Delta\bar{\varepsilon}_{el}} \tag{2}$$

where $\Delta\bar{\sigma}'$ is the variation of equivalent of normal stress which is relaxed, $\Delta\bar{\varepsilon}_{inc}$ is the accumulation of plastic strain during the relaxation time, $\Delta\bar{\varepsilon}_{el}$ is the equivalent elastic strain (equivalent elastic strain proportional to the relaxed stress, $\Delta\bar{\varepsilon}_{el} = \Delta\bar{\sigma}'/\bar{E}$) and $\Delta\bar{\varepsilon}_c$ is the equivalent creep strain.

The position of the final point in Fig. 1 may vary depending on the amount of EFU in the system. There are two critical states in this Figure. Z=1 means the there is no EFU in the system. In this circumstance stress is relaxed without any plastic strain accumulation and this is called displacement controlled condition. Also $Z = \infty$ expresses a fixed stress with plastic strain accumulation which corresponds to stress controlled conditions. The alternative interpretation for Z factor is presented by Kasahara (2001) based on strain at the initial and final of the stress relaxation as follows:

$$Z \equiv \frac{(\varepsilon)_{final} - \left(\varepsilon_{eq}^{el}\right)_{final}}{(\varepsilon)_{initial} - \left(\varepsilon_{eq}^{el}\right)_{final}} \quad \text{wher} \quad \left(\varepsilon_{eq}^{el}\right)_{final} = (\sigma)_{final}/E \tag{3}$$

The term $\left(\varepsilon_{eq}^{el}\right)_{final}$ is defined as the equivalent elastic strain at the end of relaxation process. Taleb (2013) proposed that the cyclic accumulation of the plastic strain at room temperature seems mainly due to creep. So it is possible that instead of the time variation, equation 1 be defined as the number of cycle (N). So Fig. 1 can be re-mapped as follows which is drawn for mean stress in cyclic loading:

Fig. 2: Graphical illustration of elastic follow-up in cyclic loading

In Fig. 2, points A and B represent the start and final points in cyclic loading, respectively, $\Delta\bar{\sigma}^{'}$ is reduction of mean stress and $\Delta\bar{\varepsilon}_{ratch}$ is a ratcheting strain of the specimen. Therefore, equation 2 can be written as:

$$Z = \frac{\Delta\bar{\varepsilon}_{ratch} + \Delta\bar{\sigma}^{'}/\bar{E}}{\Delta\bar{\sigma}^{'}/\bar{E}} \tag{4}$$

Therefore

$$Z\frac{\Delta\bar{\sigma}^{'}}{\bar{E}} = \Delta\bar{\varepsilon}_{ratch} + \frac{\Delta\bar{\sigma}^{'}}{\bar{E}} \tag{5}$$

So the ratcheting strain is calculated as:

$$\Delta\bar{\varepsilon}_{ratch} = -(Z-1)\frac{\Delta\bar{\sigma}^{'}}{\bar{E}} \tag{6}$$

Also equation 1 can be rewritten in the following form,

$$\frac{\partial\bar{\varepsilon}_{total}}{\partial N} + \frac{Z}{\bar{E}}\frac{\partial\bar{\sigma}_N}{\partial N} = 0 \tag{7}$$

where N is the number of cycles, $\bar{\sigma}_N$ is the reduction of mean stress during N cycles and $\bar{\varepsilon}_{total}$ is the equivalent non-linear strain (i.e. sum of accumulated plastic strain and equivalent elastic strain). Based on Fig. 2 we have:

$$\bar{\varepsilon}_{total} = \bar{\varepsilon}_{ratch} + \frac{\Delta\bar{\sigma}^{'}}{\bar{E}} \tag{8}$$

Therefore, equation 7 is simplified as:

$$\frac{\partial\bar{\varepsilon}_r}{\partial N} = -(Z-1)\frac{\partial\bar{\sigma}_N}{\bar{E}\,\partial N} \tag{9}$$

where, $\bar{\varepsilon}_r$ is the accumulated plastic strain or Ratcheting strain. This equation is similar to equation 6.

It must be noted that the strain is reduced in each cycle and the ratcheting strain is positive in equations 6 and 9.

So, the ratcheting strain is defined as a function of reduced stress in each cycle and elastic follow-up factor, Z. In fact with the concept of elastic follow-up, a simplified method is proposed for describing the ratcheting behavior of a mechanical system. Many complex rules have been proposed in the literature for modeling the ratcheting behavior of a material (chaboche 2008). However, the ratcheting behavior of the specimen in the presence of EFU can be described in a simple manner by equation 6. In this equation a non-linear event (ratcheting behavior) in the left side of the equation is described by the linear parameter (Z) on the right side.

In the next section a set of experimental tests is conducted to verify this method.

3. Specimens and material properties

In this study, two-plates in series is used to investigate the effect of elastic follow-up on ratcheting behavior under displacement-control loading conditions which is shown in Fig. 3.

Fig. 3: Two-plates in series

This specimen is composed of a high-rigidity plate with elastic manner (plate 1) and a low-rigidity plate with plastic manner (plate 2). In this condition, EFU happens in the model. It has been proven that the EFU factor Z, in this case is as equation 10 and it is a function of the geometry that does not depend on constitutive equations or non-linear events of plate 2 (Kasahara 2001).

$$Z = 1 + \frac{K_2}{K_1} \quad , \qquad K = \frac{EA}{L} \tag{10}$$

where K_2 and K_1 are the stiffnesses of plate 2 and plate 1, respectively.

The geometry of the specimen is determined in Table 1where L, H and t are the length, height and thickness, respectively.

Table 1. Dimensions of the specimen

L_1	L_2	t	H_1	H_2
5cm	4cm	3mm	(2, 3, 4 and 5)cm	1cm

Equation 10 can be written as:

$$Z = 1 + \frac{EtH_2L_1}{EtH_1L_2} = 1 + \left(\frac{H_2}{H_1}\right)\left(\frac{L_1}{L_2}\right) \tag{11}$$

Therefore, different values of Z are 1.25, 1.31, 1.42 and 1.63, which are obtained by changing the height of plate 1, H_1.

The specimens used in this study were made up of AISI 1045 steel and the material properties of this model were obtained by using an ASTM standard test procedure and the stress-strain curve for this material is shown in Fig. 4.

Based on Fig. 4, the value of elastic modulus was calculated to be E= 201GPa and the value of Poisson's ratio is considered to be v=0.3. Moreover, the value of yield stress was computed to be $\sigma_y = 324\text{MPa}$.

Fig. 4: Stress-strain curve

4. Experimental procedure

All of the tests were performed by a servo-hydraulic Zwick-Roell machine under cyclic displacement controlled loading conditions as shown in Fig. 5. This machine is equipped with a load cell with an accuracy of $\pm 1N$. Furthermore, to determine a local plastic and elastic strain in the each specimen, two strain gauges were applied. Table 2 shows the specifications of these strain gauges. The specimens and their strain gauges are shown in Fig. 6.

Fig. 5: Zwick-Roell servo-hydraulic machine.

Table 2 Strain gauge specifications

Electrical resistance (Ohm)	company	Range of strain gauge	Strain gauge model
120	TML	(10-15)%	YEFLA-2

Fig. 6: Two-plate model with various EFU parameters

Load condition shall be such that the plastic behavior occurs in plate 2 during the test time and in the meantime plate 1 is in the elastic region. So the amplitude and mean value of the induced displacement are designated to be 0.4mm and 1mm, respectively. The loading frequency in per cycles is chosen to be 2 Hz.

It should be noted that the displacement and force of the specimen are calculated by the test machine and the local strain in each plates is recorded by the data logging system.

5. Results and discussion

The main goal of the present study is to investigate the effects of elastic follow-up (elastic region around non-linear events) on the ratcheting behavior of two-plate model under displacement-controlled loading. In fact, two points of view have been studied in this paper. In other words, the results were conducted based on the global points of view which looks at the whole system (elastic region and plastic one) and also local points of view of which looks only at the plastic portion.

Fig. 7 shows the hysteresis loops for two-plates in series under displacement-controlled conditions in global points of view according to data from Zwick-Roell machine for various EFU parameters. All of the tests were conducted under unique displacement-control loading conditions. As shown in this Figure, there is no cyclic accumulation of plastic strain observed in the whole system and because of the softening behavior of the material, the force is reduced.

Fig. 7: Cyclic hysteresis loops for a specimen under displacement-control loading: (a) EFU factor is 1.25, (b) EFU factor is 1.31, (c) EFU factor is 1.42 and (d) EFU factor is 1.63

By looking locally at the system it can be seen that the plastic strain is accumulated in plate 2. This phenomenon is due to the presence of elastic follow-up in the system. In this situation, the high-rigidity and low-stress portion of system (plate 1) enhances the force to the low-rigidity and high-stress one (plate 2) and as a result, plastic strain is accumulated in the low-rigidity part of system cycle by cycle. In fact displacement-control loading shows behavior similar to force-control loading.

In Fig. 8, variation of plastic strain in plate 2 vs. the number of cycles is shown. These results are recorded by the data logging system and the strain gauges which are attached to the specimens. Based on this Figure, it can be seen that the plastic strain in plate 2 is accumulated cycle by cycle. In addition, the ratcheting strain of plate 2 by the proposed method (simplified method, i.e. equations 6 and 9) is shown in this Figure in comparison with the experimental tests. There is a good agreement between the simplified method and experimental results. It must be noted that during the tests, plate 1 must remain in the elastic region. Fig. 9 shows the maximum stress of plate 1 during the test which is less than the Yield stress of the specimen (324 MPa).

Fig. 8: Ratcheting strain of plate 2 versus the number of cycles: (a) EFU factor is 1.25, (b) EFU factor is 1.31, (c) EFU factor is 1.42 and (d) EFU factor is 1.63

Fig. 9: Maximum elastic stress of plate 1 for various EFU parameters

According to the Fig. 9, the elastic strain of plate 1 is reduced during the test. Also, with increasing the EFU parameter in the system, the amount of elastic strain and the rate of stress reduction are increased.

To determine the effects of elastic follow-up on the behavior of material in cyclic loading, the ratcheting strain of plate 2 due to the number of cycles for various EFU parameters is shown in Fig. 10. Based on this Figure, the ratcheting strain is increased with the decrease of EFU parameter (in equation 11 if the height of the elastic plate, H_1, increases, then the EFU decreases).

In Fig. 11, the variation of mean stress of plate 2 vs. the number of cycles is shown. The stress of plate 2 is reduced during the test. So the ratcheting strain by the simplified method (equation 6) is positive. Also, it is found from this Figure that if the EFU parameter is reduced, the stress of plate 2 is increased.

Fig. 10: Ratcheting strain of plate 2

Fig. 11: Mean stress plate 2 versus the number of cycles

The effect of EFU on hysteresis loop in the global points of view for the first cycle is shown in the Fig. 12. This Figure reveals that as the EFU increases, the hysteresis loop moves downward.

Fig. 12: Comparison between the simplified method and experimental results

The variation of maximum elastic strain calculated by machine test in comparison with the data of strain gauge connected to plate 1 is shown in Fig. 13. This Figure shows a good agreement between the Zwick-Roell machine test data and strain gauge data. In addition, Fig. 14 shows the effect of EFU on the maximum elastic strain in plate 1. According to this Figure, as the elastic follow-up increases the amount of elastic strain and the rate of decreasing of elastic strain increase.

Fig. 13: Variations of maximum elastic strain of plate 1 versus the number of cycles: (a) EFU factor is 1.25, (b) EFU factor is 1.31, (c) EFU factor is 1.42 and (d) EFU factor is 1.63

Fig. 14: Effect of different values of EFU factor on the elastic strain of plate 1

Based on the results of the present study and Taleb (1998) research works it is concluded that at the presence of elastic follow-up in the system, the cyclic accumulation of plastic strain or ratcheting phenomenon can occur even without a prescribed force. Also EFU has influenced the ratcheting behavior of the system.

At the end of this section it must be noted that the simplified method in the present study is based on R5 (2003) code, (Eq. 2). The Graphical illustration of the definition of elastic follow-up factor in R5 (2003) was shown in Fig. 1. So according to this definition, $\Delta\overline{\sigma}'$ in equations 2, is the variation of stress at the critical point (in the non-linear events that the strain accumulation occurs) which is dependent on the starting situation (point A) and the final situation (point B). In Fig. 1, point (A) may reach point (B) from different paths based on different loading conditions. So equation 2 is not dependent on the path and depends on the start and final conditions of loading. Therefore, this method can be extended for any loading conditions and Esq. 6 and 9 is proposed in general case. Also, it must be noted that the relevant EFU factor must be calculated for any loading conditions of any models and this involves complications. However in this study a uni-axial test has been considered in order to compare the results with experimental results.

6. Conclusions

In this paper a simplified method is proposed to investigate the effects of elastic follow-up on the ratcheting behavior of two-plates in series made up of AISI 1045 steel under displacement-control loading conditions. Moreover, a set of experimental tests were conducted by a servo-hydraulic Zwick-Roell machine in order to verify the proposed method. A data logging system and the strain gauge with the ability to work in cyclic loading were used to determine the local strain in two-plate model. The following results were obtained from this study:

- Despite the similarity between the creep behavior and cyclic accumulation of plastic strain, a new simplified method is proposed to describe the ratcheting behavior in the case of elastic follow-up under the displacement controlled loading.
- Based on Fig. 8, there is a good agreement between the ratcheting strain obtained by experimental tests and the proposed method (Equations 6 and 9).
- In the presence of elastic follow-up phenomenon in two-plate model, the cyclic accumulation of plastic strain occurs under displacement-control loading conditions (Fig. 10) and the ratcheting strain is increased with the decrease of elastic follow-up parameter.
- Fig. 12 reveals that as the elastic follow-up increases, the hysteresis loop moves downward.
- According to Fig. 14, as the elastic follow-up increases the amount of elastic strain and the rate of decreasing of elastic strain increase.

References

Robinson EL (1939) The Resistance to Relaxation of Materials at High Temperature Trans ASME 61:543–554.

Robinson EL (1955) Steam-Piping Design to Minimize Creep Concentrations Trans ASME 77:1147–1162.

Boyle JT, Nakamura K (1987) The Assessment of Elastic Follow-Up in High Temperature Piping Systems—Overall Survey and Theoretical Aspects Int J Pressure Vessels Piping 29(3):167-194.

Kasahara N (2001) Strain Concentration at Structural Discontinuities and its Prediction Based on Characteristics of Compliance Change in Structures JSME International Journal Series A 44(3):354–361.

Teramae T (1983) A Simplified Method for Elastic Follow-Up Analysis of Elevated Temperature Piping Systems Int J Pressure Vessels Piping 12:29–41.

Dhalla A K, Jones GL (1986) ASME Code Classification of Pipe Stresses: a Simplified Elastic Procedure Int J Pressure Vessels Piping 26:145–166.

Roche RL (1986) Estimation of Piping Elastic Follow-Up by Using Conventional Computations Int J Pressure Vessels Piping 26:53–78.

Roche RL (1988) Modes of Failure-Primary and Secondary Stresses J Pressure Vessel Technol 110(3):234–239.

Dhalla AK (1991) Stress Classification for Elevated Temperature Service J Pressure Vessel Technol 113(4):488–496.

Hadidi-Moud S, Smith DJ (2008) Use of Elastic Follow-Up in Integrity Assessment of Structures International Conference on Pressure Vessels and Piping (ASME-PVP2008-61754) Chicago IL July 17–31.

Arid CJ, Hadidi-Moud S, Truman CE, Smith DJ (2008) Impact of Residual Stress and Elastic Follow-Up on Fracture J ASTM Int 5(8):14.

Fujioka T (2013) Simplified Estimate of Elastic-Plastic J-integral of Cracked Components Subjected to Secondary Stresses by the Enhanced Reference stress Method and EFU Factors Int J Pressure Vessels and Piping 108-109: 28-39.

Ainsworth RA (2012) Consideration of EFU in the Treatment of Combined Primary and Secondary Stresses in Fracture Assessment Eng Fracture Mech 96:558-569.

Boyle JT (2013) A re-Assessment of EFU in high Temperature Piping Int J Pressure Vessels and Piping 108-109:7-12.

Ohno N (1997) Recent progress in constitutive modeling for ratcheting Mater Sci Res Int 3:1–9.

Chen X, Yu DH, Kim KS (2005) Experimental study on ratcheting behavior of eutectic tin–lead solder under multiaxial loading Mater Sci Eng A 406:86–94.

Chen G, Chen X, Niu CD (2006) Uniaxial ratcheting behavior of 63Sn37Pb solders with loading histories and stress rates Materials Science and Engineering 421:238–244.

Jain AK, Hanson RD, Goel SC (1978) Inelastic response of restrained steel tubes J Struct Div ASCE 104:897–910.

Chen G, Shan SH, Chen X, Yuan H (2009) Ratcheting and fatigue properties of the high-nitrogen steel X13CrMnMoN18-14-3 under cyclic loading Compute Mater Sci 46(3):572–8.

Shariati M, Hatami M, Torabi H, Epakchi HR (2012) Experimental and numerical investigations on the ratcheting characteristics of cylindrical shell under cyclic axial loading Structural Engineering and Mechanics 44(6):753-762.

Shariati M, Kolasangiani K, Norouzi G, Shahnavaz (2014) A. Experimental study of SS316L cantilevered cylindrical shells under cyclic bending load Thin-Walled Structures 82:124-131.

Chaboche JL, Lemaitre J (1990) Mechanics of Solid Materials Cambridge University Press Cambridge UK.

Ohno N (1998) Constitutive Modeling of Cyclic Plasticity with Emphasis on Ratcheting Int J Mech Sci 40(2-3):251-261.

Abdel-Karim M, Ohno N (2000) Kinematic hardening model suitable for ratcheting with steady-state Int J Plast 16(3/4):225-240.

Chaboche JL (2008) A review of some plasticity and viscoplasticity constitutive theories International Journal of Plasticity 24:1642–1693

Halama R, Fusek M, Poruba Z (2016) Influence of Mean Stress and Stress Amplitude on Uniaxial and Biaxial Ratcheting of ST52 Steel and Its Prediction by the AbdelKarim–Ohno Model Int J of Fatigue 91(2):313-321.

Taleb L, Cousin M, Jullien JF (1998) Metallic structures subjected to cyclic loadings—I. Inadequacy of the elastic analysis for the steady state assessment International Journal of Pressure Vessels and Piping 75:173–180.

Taleb L, (1998) Metallic structures subjected to cyclic loadings—II A new approach to assess the steady state assessment International Journal of Pressure Vessels and Piping 75:181–190.

British Energy, Gloucester, UK (2003) R5 Assessment procedure for the high temperature response of structures Issue 3 British Energy Generation Limited.

Taleb L (2013) About the cyclic accumulation of the inelastic strain observed in metals subjected to cyclic stress control International Journal of Plasticity 43:1-19.

Figure caption

Fig. l: Graphical illustration of the definition of elastic follow-up factor in R5 (2003).

Fig. 2: Graphical illustration of elastic follow-up in cyclic loading

Fig. 3: Two-plates in series

Fig. 4: Stress-strain curve

Fig. 5: Zwick-Roell servo-hydraulic machine.

Fig. 6: Two-plates with various EFU parameters

Fig. 7: Cyclic hysteresis loops for a specimen under displacement-control loading: (a) EFU factor is 1.25, (b) EFU factor is 1.31, (c) EFU factor is 1.42 and (d) EFU factor is 1.63

Fig. 8: The ratcheting strain of plate 2 versus the number of cycles: (a) EFU factor is 1.25, (b) EFU factor is 1.31, (c) EFU factor is 1.42 and (d) EFU factor is 1.63

Fig. 9: Maximum elastic stress of plate 1 for various EFU parameters

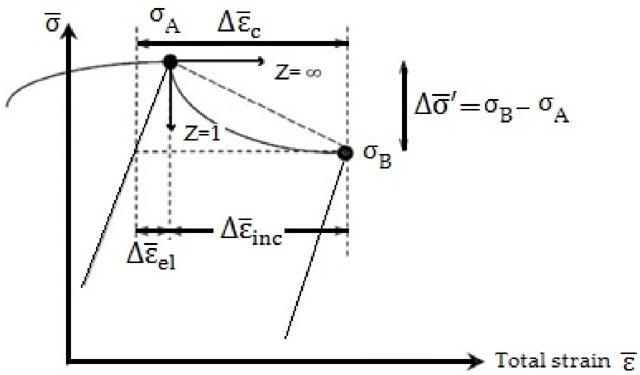
Fig. 10: the ratcheting strain of plate 2

Fig. 11: Mean stress of plate 2 versus the number of cycles

Fig. 12: Comparison between the simplified method and experimental results

Fig. 13: Variation of maximum elastic strain of plate 1 versus the number of cycles: (a) EFU factor is 1.25, (b) EFU factor is 1.31, (c) EFU factor is 1.42 and (d) EFU factor is 1.63

Fig. 14: Effect of different values of the EFU factor on elastic strain of plate 1



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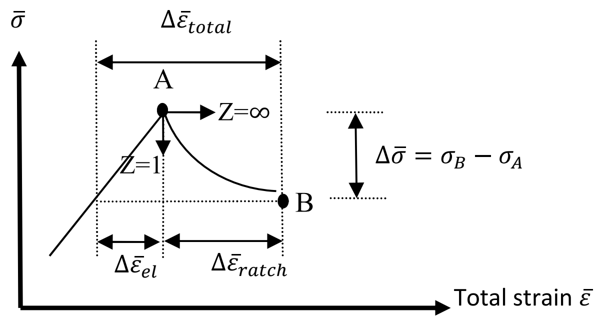


Fig. 2: Graphical illustration of elastic follow-up in cyclic loading

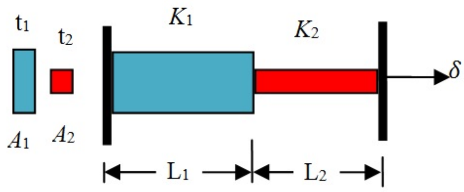


Fig. 3: Two-plates in series

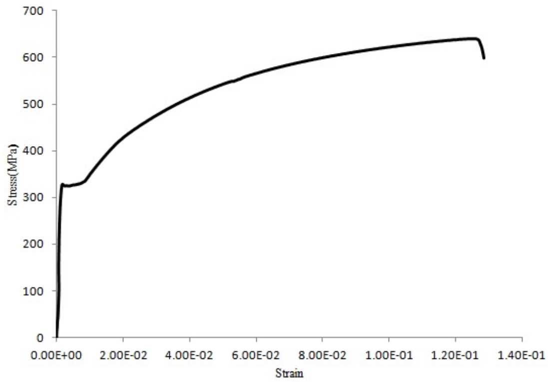


Fig. 4: Stress-strain curve

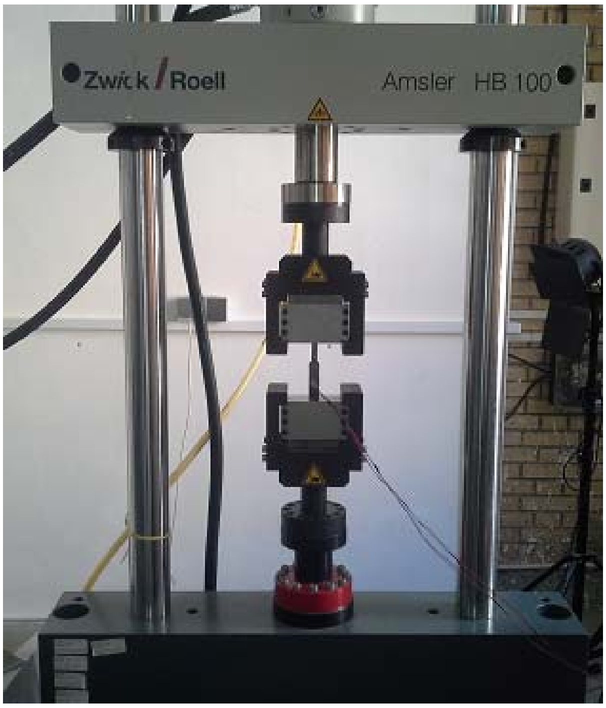
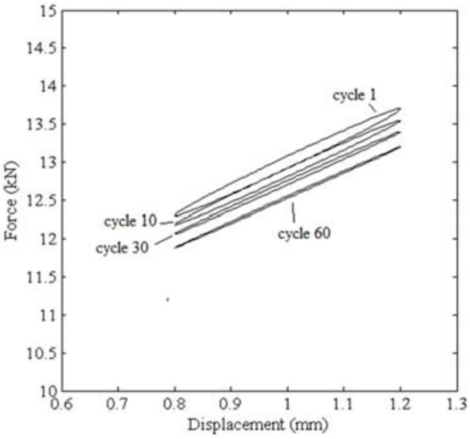
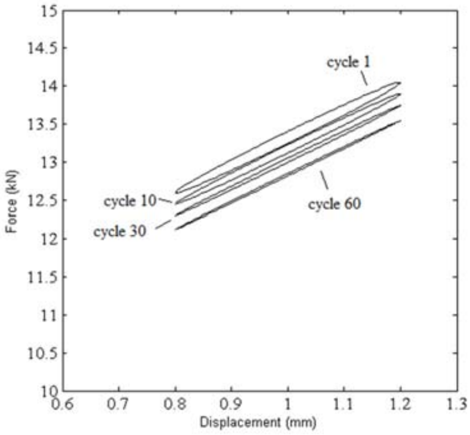


Fig. 5: Zwick-Roell servo-hydraulic machine.

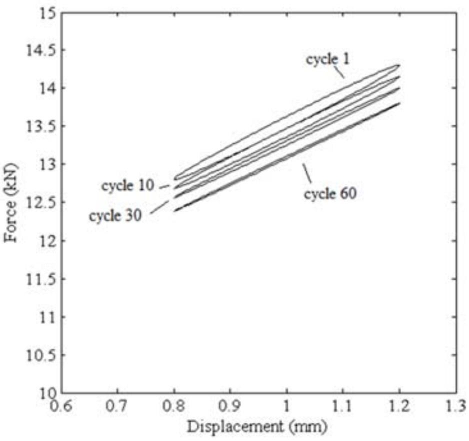
Fig. 6: Two-plates with various EFU parameters

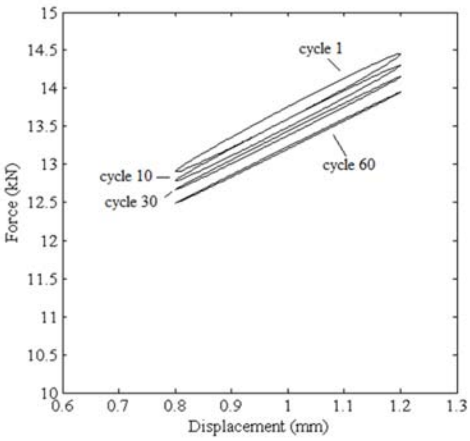


(a)



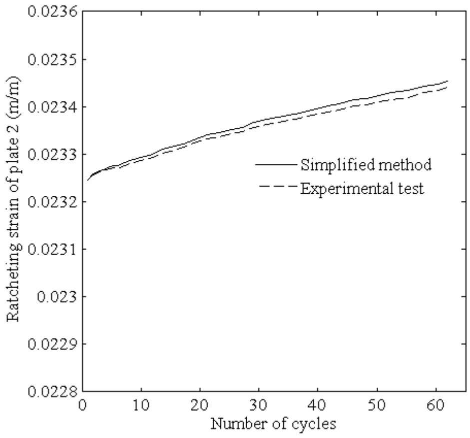
(b)



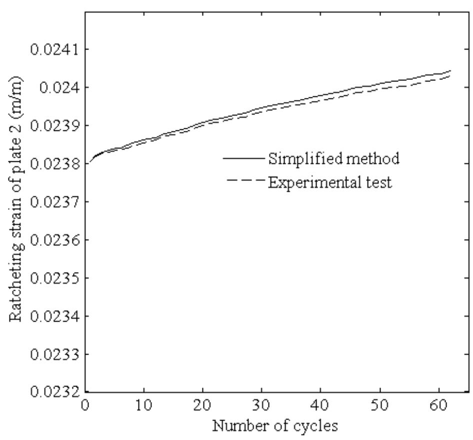


(c) (d)

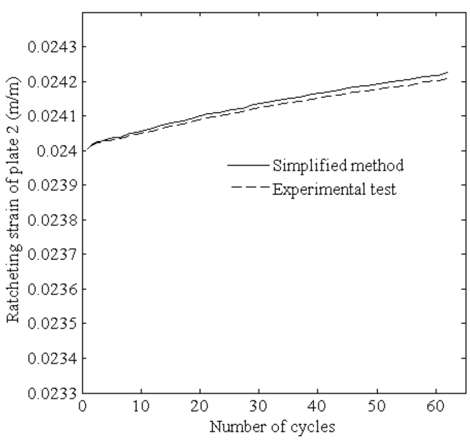
Fig. 7: Cyclic hysteresis loops for a specimen under displacement-control loading: (a) EFU factor is 1.25, (b) EFU factor is 1.31, (c) EFU factor is 1.42 and (d) EFU factor is 1.63



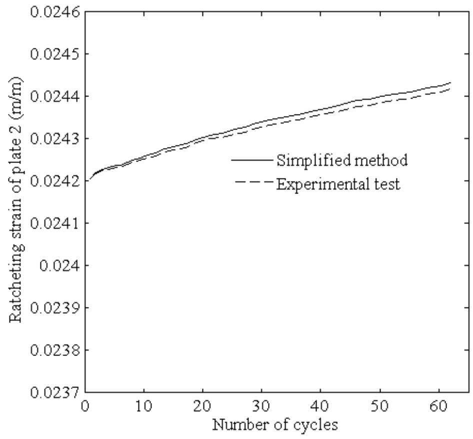
(a)



(b)



(c)



(d)

Fig. 8: The ratcheting strain of plate 2 versus the number of cycles: (a) EFU factor is 1.25, (b) EFU factor is 1.31, (c) EFU factor is 1.42 and (d) EFU factor is 1.63

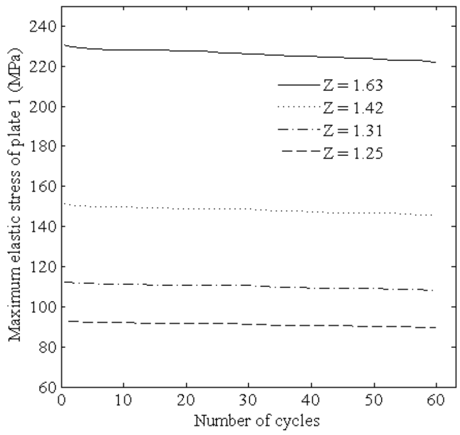


Fig. 9: Maximum elastic stress of plate 1 for various EFU parameters

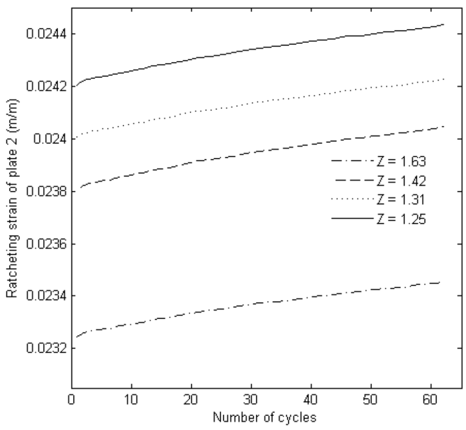


Fig. 10: the ratcheting strain of plate 2

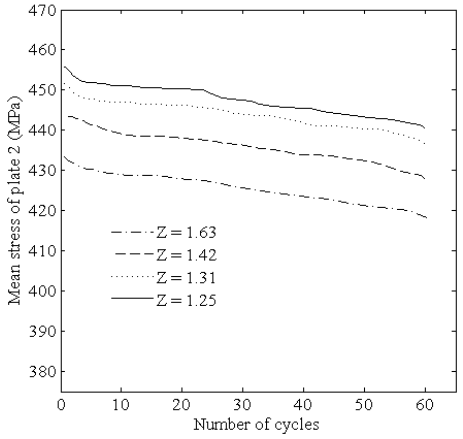


Fig. 11: Mean stress of plate 2 versus the number of cycles

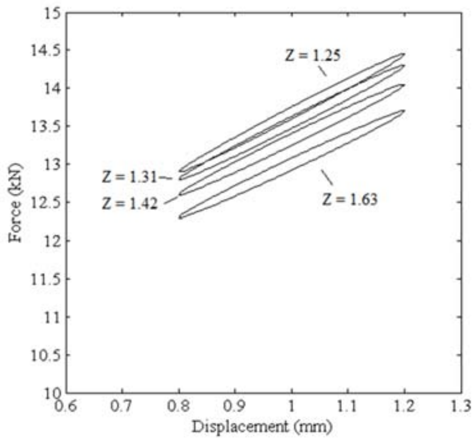


Fig. 12: Comparison between the simplified method and experimental results

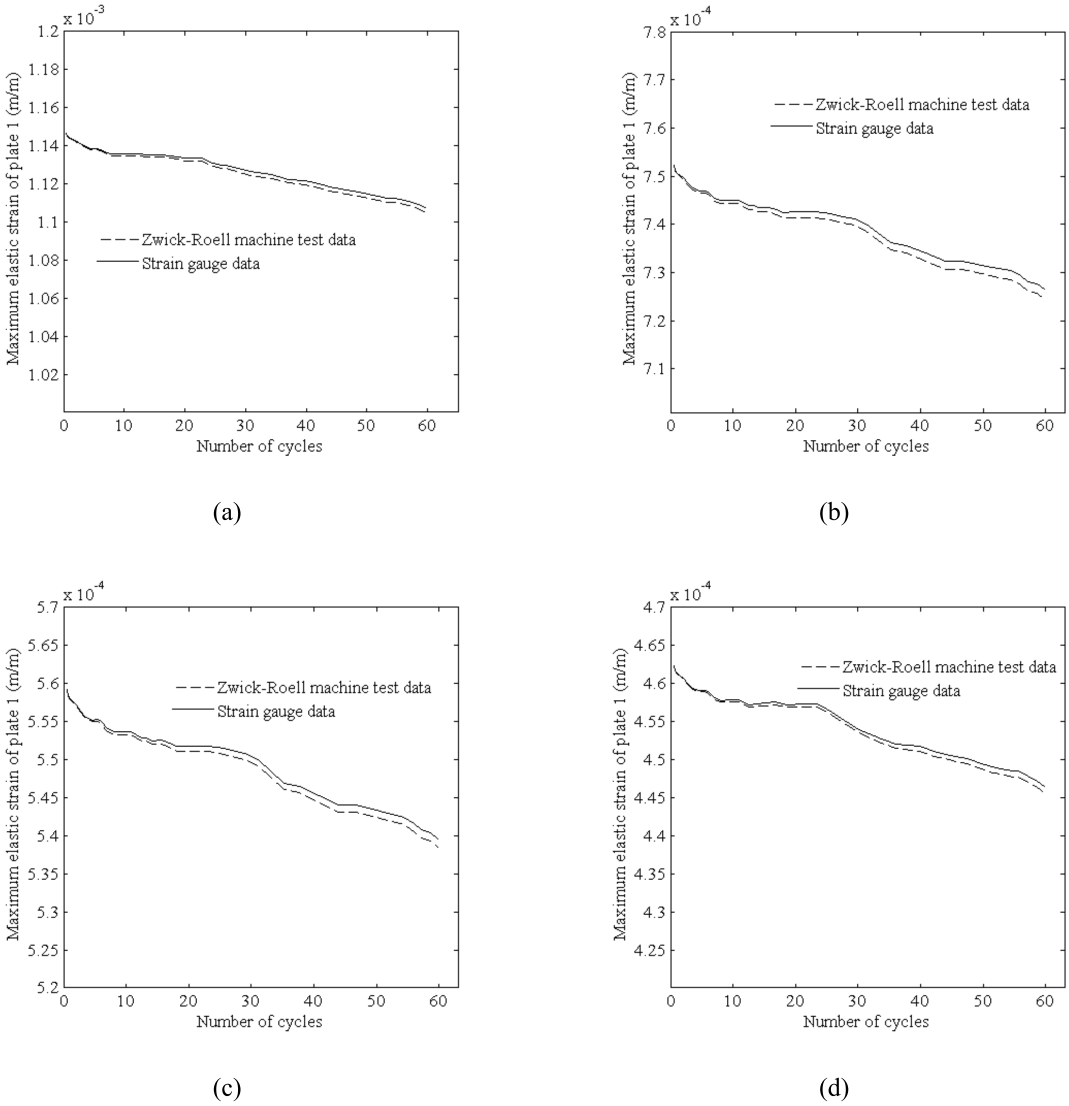


Fig. 13: Variation of maximum elastic strain of plate 1 versus the number of cycles: (a) EFU factor is 1.25, (b) EFU factor is 1.31, (c) EFU factor is 1.42 and (d) EFU factor is 1.63

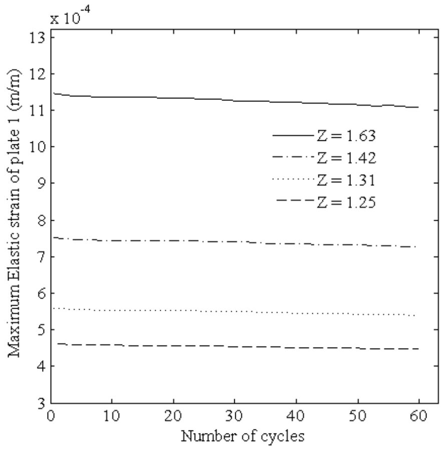


Fig. 14: Effect of different values of the EFU factor on elastic strain of plate 1