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Fatigue Life Evaluation of Single and Two Riveted Coach Peel Joints Using Strain-Life Criteria

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ABSTRACT: In this paper, experimental investigation was performed to estimate fatigue life of single and double riveted coach peel joints of 2024 aluminum alloy. Load controlled fatigue tests were conducted with load ratio and frequency of 0.1 and 10 Hz, respectively. Failure of the specimens revealed three major modes of folded region fracture (A-type), fracture from edge of the rivet hole (B-type) and mixed mode fracture (A & B). Although all failure modes contributes equally in single riveted joint, mixed mode fracture was observed as dominant mode in two riveted ones. A numerical approach is applied to estimate fatigue life of riveted coach peel joints. Finite element analysis was implemented by ABAQUS as the first step of this approach to estimate stress distribution, stress concentration factor, stress and strain amplitude. Fatigue lives were then calculated using three fatigue life theories of Monson-Hirschberg, Smith-Watson-Topper and Morrow. Finally, good accordance between numerical and experimental results revealed that the finite element approach combined with fatigue life theories is capable for fatigue life prediction. It is concluded that adding a rivet in longitudinal direction to the single riveted coach peel joint decreases the life cycles by increasing the stress concentration factor. Moreover, results of finite element approach showed that Monson-Hirschberg and experimental data has the best agreement in compare with SWT and Morrow.

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1- Introduction

Automotive industry aims at providing lighter structural parts in order to reduce fuel consumption and air pollution. According to environmental regulations, aluminum and high strength steel are widely used in manufacturing car structures to supply suitable strength and weight. Spot welding is known as a dominant joining method for steel structural parts. But this joining method is not proper for aluminum joints because of surface sensitivity and short electrode tip life [1,2]. Riveting is considered as an appropriate method for connecting elements of automotive and aircraft structural components because of their durability, high resilience and flexibility [3,4]. As riveted Coach Peel (CP) is a common joint configuration in industries such as automotive, it is significant to investigate the static and fatigue behavior of these joints. Additionally, it is cost and time effective to develop a finite element approach to estimate fatigue life of the coach peel joint by implementing fatigue life criteria.

Fung and Smart [5,6] carried out numerical and experimental study on the effect of clearance fit, friction and clamping force on the fatigue life of the riveted lap joints. Booth et al. [7] performed a comparative study on static and fatigue strength of self-piercing riveting and resistance spot welding. They found that self-piercing riveting has superior fatigue strength than resistance spot welding. Li and Fatemi [8] conducted experimental investigation on evaluating static and fatigue strength of coach peel pop rivet and coach peel self-piercing joints by considering variations in plate thickness. They observed that the strength of coach peel self-piercing rivet was lower than coach peel pop rivet. But coach peel self-piercing rivet showed higher fatigue performance than coach peel pop rivet specimens. Mohammadpour et al. [9] performed a finite element analysis to predict fatigue life of a riveted coach peel joint by applying different multi-axial fatigue criteria. Moreover, there are many research works that investigated on stress-controlled cyclic loading of engineering materials and the ratcheting behavior both experimentally and numerically [10-13]. As it is mentioned, most of previous research works have focused on fatigue life evaluation of different coach peel joint types by considering the effect of various parameters such as clearance fit, clamping force, friction force and different thicknesses. The present paper aims to achieve a life prediction approach using finite element modeling and fatigue life criteria. Besides, experimental fatigue tests are performed and the results of numerical approach are compared with experimental data to reveal the appropriate criteria in life prediction of single riveted coach peel joint

In the present paper, fatigue lives of coach peel joint configurations with single and two rivets were achieved both experimentally and numerically. Furthermore, the numerical procedure includes the implementation of finite element method and fatigue life criteria. Fatigue tests have been performed on riveted coach peel joints of 2024 aluminum alloy with single and two rivets using servo-hydraulic testing machine. Post failure observations were conducted to categorize failure modes for single and two riveted CP configurations. Finite element model of CP joints has been presented to simulate stress distribution by considering nonlinear behavior of the material. As the critical structural location in fatigue design could be a notch, hole or etc. in which plastic strains are surrounded by elastic material, this phenomenon could be modeled using total strain range. This strain range can be described by plastic part as Coffin-Manson, by considering both elastic and plastic strains as in

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Manson-Hirschberg (MH), by accounting the mean stress effect as Morrow, and by the combined effect of cyclic strain range and maximum stress as Smith-Watson-Topper (SWT). Therefore, three strain-life criteria (Manson-Hirschberg, Smith-Watson-Topper, and Morrow) were applied in order to predict life cycles. The comparison of life cycles between experimental data and fatigue life criteria was conducted in order to show the performance of finite element model and to achieve the suitable life estimation theory.

2- Experimental Procedure

2- 1- Materials and methods

Flat specimens of Al-2024-T3 alloy were annealed at 413 Centigrade degrees before folding and preparing coach peel (L-shape) configuration in order to prevent the early failure of test coupons from folded region. Fig. 1 shows the geometrical parameters of flat and coach peel specimens. The 5 mm rivet hole with 0.02 mm clearance fit was drilled and steel rivet with 7 mm shank length was selected for manufacturing the joints. Riveting process is performed by applying 7 kN force using hydraulic press machine. Tension test is conducted according to ASTM E8 [14] in order to achieve stress-strain behavior of 2024 Aluminum alloy (Fig. 2).

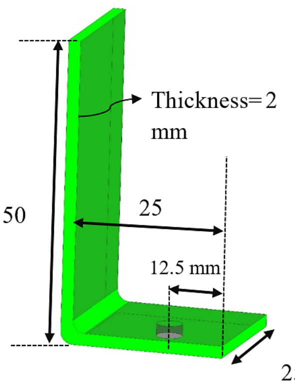


Fig. 1. Geometrical dimensions of L-shape specimen.

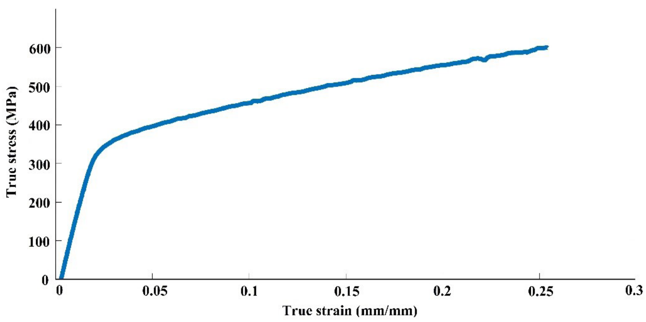


Fig. 2. True stress-strain curve for Al2024-alloy.

All coach peel specimens were fatigue tested on Zwick/Roell Amsler HB100 (Germany) servo-hydraulic testing machine (Fig. 3) with 10 kN load cell. Fatigue tests were conducted in load-control condition, sinusoidal waveform loading with load ratio of 0.1 (maximum load of 1.5 kN) and 10 Hz frequency.

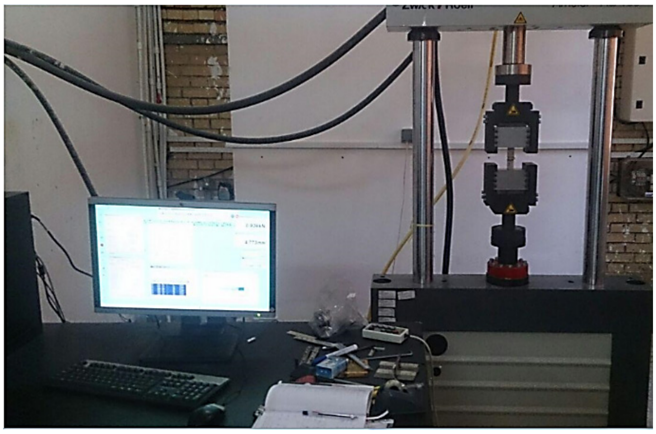


Fig. 3. Fatigue testing machine and the coach peel specimen

3- Fatigue Life Criteria

Fatigue lives of single and two riveted CP joints were calculated by means of three life prediction approaches. Manson-Hirschberg, Smith-Watson-Topper and Morrow criteria was used as low cycle fatigue criteria to estimate life cycles.

3- 1- Manson-Hirschberg

The strain-life method in fatigue life estimation of engineering materials can be categorized in two parts. The first part was presented by Basquin (Eq. (1)) [15,16] which is indicated to S-N analysis, but it is solved in terms of strain.

$$\frac{\Delta\sigma}{2} = \sigma_a = E\,\Delta\varepsilon_e = \sigma'_f\,(2N_f)^b \tag{1}$$

where $\Delta\sigma/2$ is the stress amplitude, $2N$ represents reversals to failure and b is fatigue strength exponent. The second part relates to plastic fatigue properties that was presented by Coffin-Manson (Eq. (2)) [15,16].

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon'_f\,(2N_f)^c \tag{2}$$

where ε'_f and c are fatigue ductility coefficient and fatigue strength exponent, respectively. The total strain amplitude, presented by Manson-Hirschberg [15], achieves by combining Basquin and Coffin-Manson equations (Eq. (3)).

$$\frac{\Delta\varepsilon}{2} = \varepsilon_a = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma_f{}'}{E}(2N_f)^b + \varepsilon_f{}'\,(2N_f)^c \tag{3}$$

3- 2- Smith-Watson-Topper

Smith, Watson and Topper presented a relation that contains cyclic strain range and maximum stress. This fatigue life model states that the crack propagation could be controlled by maximum stress and strain planes. The Smith-Watson-Topper relation (Eq. (4)) is as follows [17]:

$$\sigma_{\max}\,\varepsilon_a\,E = (\sigma'_f)^2\,(2N)^{2b} + \sigma'_f\,\varepsilon'_f\,E\,(2N)^{b+c} \tag{4}$$

where ε'_f, σ'_f, b, c and E are the fatigue ductility coefficient, fatigue strength coefficient, fatigue strength exponent and Young modulus, respectively.

3- 3- Morrow

The prediction of Morrow model states that the mean stress has considerable effect on longer lives and has little effect on shorter lives. The Morrow's strain-life prediction model (Eq. (5)) is as follows [18]:

$$\frac{\Delta\varepsilon}{2} = \varepsilon_a = \frac{\sigma'_f - \sigma_m}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c \tag{5}$$

where σ_m is mean stress.

3- 4- Theoretical approach for calculating fatigue life parameters

Fatigue parameters should be calculated as the first step of predicting life cycles. Cyclic strength coefficient and the cyclic strain hardening exponent can be calculated according to Eq. (6) [19]:

$$n' = \frac{b}{c} \quad , \quad K' = \frac{\sigma'_f}{{\varepsilon'_f}^{n'}} \tag{6}$$

where K', n', σ'_f, ε'_f, b and c stands for the cyclic strength coefficient, cyclic strength hardening exponent, fatigue strength coefficient, fatigue ductility coefficient, fatigue strength exponent and fatigue ductility exponent, respectively. The amounts of σ'_f, ε'_f, b and c for Al-2024 are achieved as 779 MPa, 0.41, -0.089 and -0.664, respectively [20]. Therefore, n' and K' are calculated as 0.134 and 877.86.
The amount of stress amplitude (σ_a) can be calculated by Eq. (7) and consequently ε_a is calculated from Ramberg-Osgood equation (Eq. (8)) [16].

$$\frac{{\sigma_a}^2}{E} + \sigma_a\left(\frac{\sigma_a}{K'}\right)^{\frac{1}{n'}} = \frac{(K_t S_a)^2}{E} \tag{7}$$

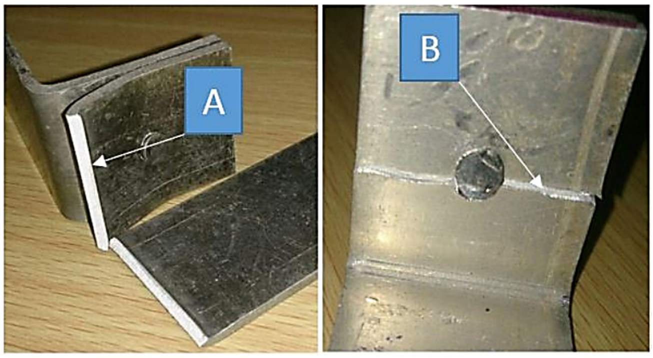
$$\varepsilon_a = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{\frac{1}{n'}} \tag{8}$$

where S_a is the nominal stress amplitude. As the final step, Fatigue life can be calculated by substituting ε_a in Manson-Hirschberg, SWT and Morrow relations.

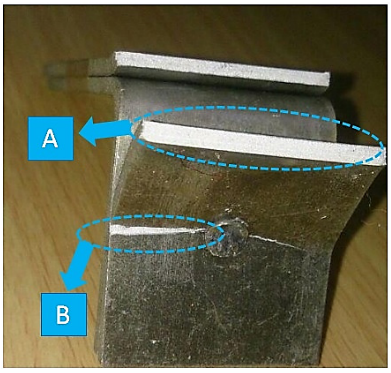
4- Results and Discussion

4- 1- Fatigue failure of coach peel joints

Three major failure types were observed for single riveted CP specimens (Fig. 4): fracture at folded region (A-type failure), fracture from rivet hole (B-type failure) and mixed mode failure (both A and B type). It should be noted that there was no artificial defects such as pre-cracks in these failure locations. Therefore, the cracks were initiated from the folded region and rivet hole and then propagated until complete fracture.
The results of fatigue lives and failure modes on single and two riveted CP joints are presented in Fig. 5. The first category of specimens (C11, C21 and C31) represents the single riveted CP joint and the second category (C12, C22, C32) is related to the riveted CP joint with two rivets. Results of fatigue tests showed that three failure types were observed for single riveted CP joints. Although thermal treatment was conducted on Al-2024 alloy specimens, failure of CP joint from folded region of L-shape plate (type-A failure) reveals that stress concentration in folded region is more than rivet's hole. Damage initiation in mixed mode case has accelerated the damage propagation and consequently has resulted in lower fatigue life than other failure types. Major failure type in the second category of specimens (C12, C22, and C32) was observed to be at mixed mode. Fig. 6 shows the fatigue testing of single and two riveted CP joints. According to Figs. 5 and 6, it is obvious that two riveted CP joints have lower fatigue life than single riveted joints because more stress



(a)



(b)

Fig. 4. Types of failure in single riveted coach peel joint, a) A: fracture at folded region, B: fracture of plate from edge of the hole, b) mixed mode fracture (A&B).

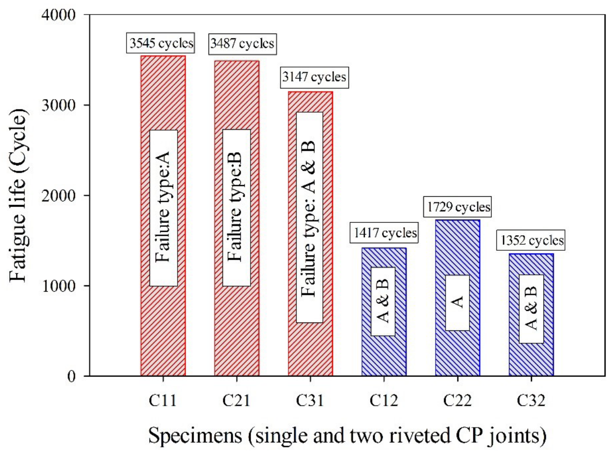
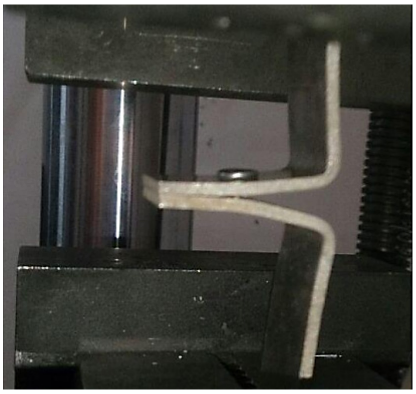
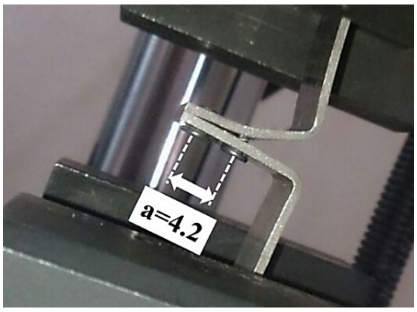


Fig. 5. Fatigue life cycle and failure modes for single and two riveted CP joint.

concentration was induced by adding a rivet in longitudinal direction. Thus, it can be concluded that adding a rivet in longitudinal path is not appropriate for manufacturing coach peel joints.



(a)



(b)

Fig. 6. Fatigue testing of riveted coach peel joints, a) Single riveted, b) Two riveted.

4- 2- Numerical Results

4- 2- 1- Finite element modeling

Finite element method was applied in order to obtain stress distribution in the joint and to calculate fatigue life using low cycle fatigue criteria. Single and multi-riveted coach peel joints were modeled by ABAQUS finite element commercial software. Material properties were defined according to stress-strain behavior of Al-2024 alloy. Explicit surface to surface contact was defined between rivet-hole, rivet-plate and plate-plate interfaces. The numerical simulation was carried out through dynamic/explicit step and eight node, reduced integrated elements of C3D8R type were selected for finite element analysis. The loading was applied in tension to the upper part and the displacement and rotation of the lower part were constrained as the testing specimen is fixed in gripper. As previously mentioned, the maximum fatigue load of 1.5 kN was considered as maximum fatigue load. According to loading area of 50 mm2, the stress field of 30 MPa was applied to the model (Fig. 7).

4- 2- 2- Results of finite element modeling and numerical procedure

The results of Von-Mises stress distributions for a single riveted CP joint is shown in Fig. 8. The 30 MPa tension is applied as nominal stress to the single riveted coach peel joint. As it is shown in Fig. 8, the maximum stress around rivet's hole is 398.7 MPa. Thus, the stress concentration

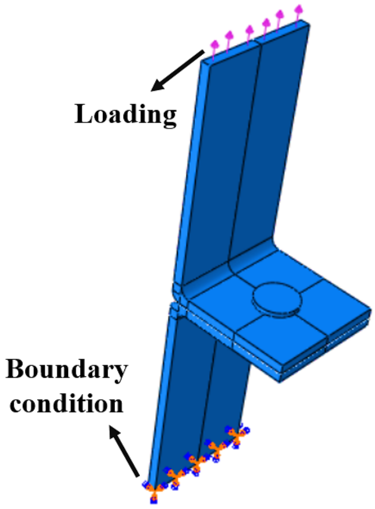


Fig. 7. Loading and boundary conditions.

factor for this configuration is estimated as 13. Stress amplitude (σ_a) is then calculated by substituting the stress concentration factor in Eq. (7). Afterwards, strain amplitude (ε_a) could be calculated by substituting stress amplitude, cyclic strength coefficient and cyclic strength hardening exponent in Ramberg-Osgood equation. According to the stress distribution of riveted coach peel joint with two rivets (Fig. 9), the maximum stress is estimated as 425.1 MPa. Moreover, stress and strain amplitudes were calculated as 378.4 MPa and 0.0071 MPa, respectively. Consequently, fatigue life cycles were calculated for single and two riveted coach peel joints.

Combination approach of finite element analysis and strain-life theories resulted in fatigue lives for single and two riveted CP joints (Fig. 10). As it can be seen in Fig. 10, life cycles are decreased in two riveted CP joint because the second hole is closer to folded region (L-shape region) of the joint and this increases stress field and leads to lower fatigue life. The comparison between experimental and numerical life cycles for single riveted CP joint is shown in Fig. 11. It can be inferred that life estimation using Manson-Hirschberg criteria have better accordance to the mean of experimental life cycle because it considers both the elastic and plastic

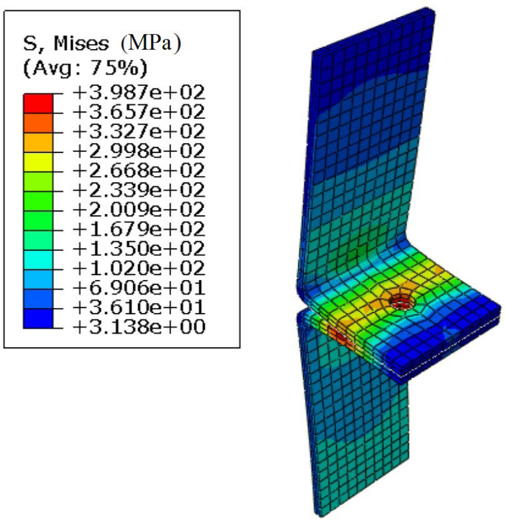


Fig. 8. Stress distribution in single riveted coach peel joint.

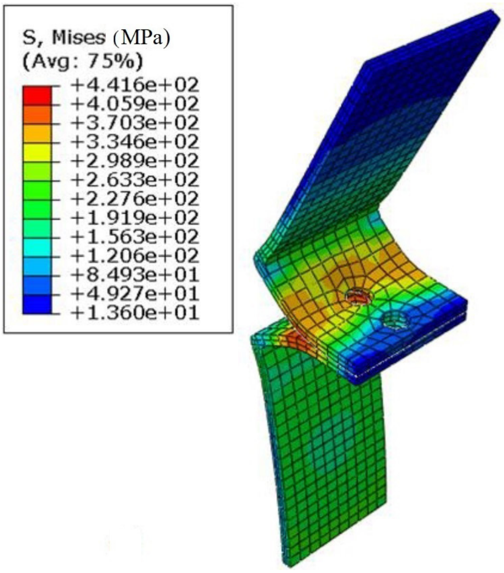


Fig. 9. Stress distribution in riveted coach peel joint with two rivets.

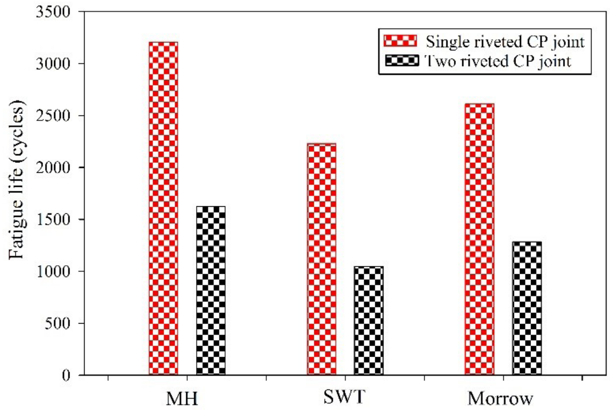


Fig. 10. Finite element results of fatigue life cycle for single and two riveted coach peel joints.

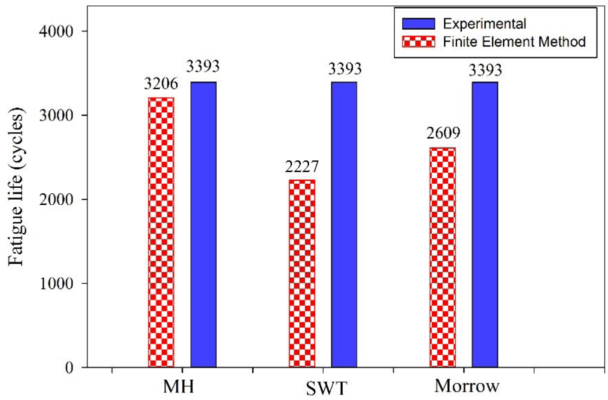


Fig. 11. Comparison between numerical and experimental results for single riveted CP joints.

strain amplitudes. The difference between Morrow's fatigue life and experimental data is because the mean stress does not has significant effect on results of Morrow equation in short fatigue lives. Fig. 12 also shows the agreement between finite element and experimental results of fatigue life for CP joint with two rivets. As it is illustrated in Figs. 11 and 12, it is obvious that MH criterion has achieved the best accordance to experimental data and can be applicable for life prediction. On the other hand, SWT criterion gives the most conservative life estimation for single and two riveted CP joints and consequently is not appropriate for CP design.

5- Conclusions

In this paper, an experimental study is carried out in order to achieve fatigue life of coach peel joints with single and two rivets. Fatigue failure mode observations revealed that there are three failure modes for single riveted CP joint (A: fracture of plate from hole edge, B: fracture from folded region and mixed mode of A & B) and one dominant failure mode (mixed mode: fracture from hole edge and folded region) for two riveted CP joint. Although all failure modes were observed in single riveted CP joint, mixed mode failure (both A & B) was the dominant mode in two riveted CP joints. It is also observed that the fatigue life of CP joint decreases by adding a rivet in longitudinal direction. Fatigue life estimations were performed using three low-cycle fatigue theories of Manson-Hirschberg, Smith-Watson-Topper and Morrow. A finite element model was presented to determine stress distribution, stress concentration factor, stress amplitude and strain amplitude. These parameters are then used to calculate fatigue life through each criterion. As a good accordance was found between numerical results and fatigue life, it could be concluded that the finite element approach combined with strain-life theories is capable for fatigue life estimation of coach peel joints. It can also be inferred that the Monson-Hirschberg criterion has better accordance to experimental fatigue data than SWT and Morrow and consequently it can be considered as an appropriate criterion in fatigue life prediction.

References

[1] X. Sun, E.V. Stephens, M.A. Khaleel, Fatigue behaviors of self-piercing rivets joining similar and dissimilar sheet materials, *International Journal of Fatigue*, 29(2) (2007) 370-386.

[2] D. Li, L. Han, M. Thornton, M. Shergold, Influence of rivet to sheet edge distance on fatigue strength of self-piercing riveted aluminum joints, *Materials Science and Engineering A*, 558 (2012) 242-252.

[3] P. Zamani, S. Mohajerzadeh, R. Masoudinejad, Kh. Farhangdoost, Numerical investigation on optimizing fatigue life in a lap joint structure, World Academy of Science, Engineering and Technology, International Journal of Civil, Environmental, Structural, *Construction and Architectural*, 9 (2015) 647-653.

[4] L. Han, M. Thornton, M. Shergold, A comparison of mechanical behavior of self-piercing riveted and resistance spot welded aluminum sheets for the automotive industry, *Materials & Design*, 31(3) (2010) 1457-1467.

[5] C.P. Fung, J. Smart, Riveted single lap joints. Part 1: Fatigue life prediction, Proceedings of the institution of mechanical engineers, *part G* (*Journal of Aerospace Engineering*), 211 (1) (1997) 13-27.

[6] C.P. Fung, J. Smart, Riveted single lap joints. Part 2: A numerical parametric study, Proceedings of the institution

of mechanical engineers, *part G* (*Journal of Aerospace Engineering*), 211 (2) (1997) 123-128.

[7] G.S. Booth, , C.A. Olivier, , S.A. Westgate, , F. Liebrecht, , S. Braunling, Self piercing riveted joints and resistance spot welded joints in steel and aluminum, In: *Proceedings of the International Body Engineering Conference*, Detriot, MI; SAE Paper No. 2000-01-2681, 2000.

[8] B. Li, , A. Fatemi, An experimental investigation of deformation and fatigue behavior of coach peel riveted joints, *International Journal of Fatigue*, 28(1) (2008) 9-18.

[9] M. Mohammadpour, M.H. Kalajahi, R.H.Oskouei, M. Shakouri, Fatigue life estimation of coach peel riveted joints using multi-axial fatigue criteria, *Materials & Design*, 62 (2014) 327-33.

[10] M. Shariati, H. Hatami, H. Yarahmadi, H.R. Eipakchi, An experimental study on the ratcheting and fatigue behavior of polyacetal under uniaxial cyclic loading, *Materials & Design*, 34 (2011) 302-312.

[11] M. Shariati, H. Hatami, Experimental study of SS304L cylindrical shell with/without cutout under cyclic axial loading, *Theoretical and Applied Fracture Mechanics*, 58 (1) (2012), 35-43.

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

[13] M. Shariati, H. Hatami, H.R. Eipakchi, H. Yarahmadi, H. Torabi, Experimental and numerical investigations on softening behavior of POM under cyclic strain-controlled loading, *Polymer-Plastics Technology and Engineering*, 50 (15) (2011), 1576-1582

[14] ASTM E8. Standard test methods for tension testing of metallic materials, *ASTM International*, (2009)

[15] W. Cui, A state-of-the-art review on fatigue life prediction methods for metal structures, *Journal of Marine Science and Technology*, 7(1) (2002) 43-56.

[16] A. Fatemi, A. Plaseied, A.K. Khosrovaneh, D.Tanner, Application of bi-linear log-log S-N model to strain-controlled fatigue data of aluminum alloys and its effect on life predictions, *International Journal of Fatigue*, 27(9) (2005) 1040-1050.

[17] K.N. Smith, P. Watson, T.H. Topper, A stress-strain function for the fatigue of metals, *Journal of Materials*, 5 (1970) 767-778.

[18] A. Ince, G.Glinka, A modification of Morrow and Smith-Watson-Topper mean stress correction models, *Fatigue and Fracture of Engineering Materials & Structures*, 34(11) (2011) 845-867.

[19] Z. Zhang, Y. Qiao, Q. Sun, C. Li, J. Li, Theoretical estimation to the cyclic strength coefficient and the cyclic strain-hardening exponent for metallic materials: Preliminary study, *Journal of Materials Engineering and Performance*, 18(3) (2009) 245-254

[20] R.H. Richman, W.P. McNaughton, Correlation of cavitation erosion behavior with mechanical properties of metals, *Wear*, 140(1) (1990) 63-82.

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