Materials Research Express

Effect of low-velocity impact on mechanical property and fatigue life of DP590/AA6061 self-piercing riveted joints

Yi-Guang Zhao*, Zhi-Chao Huang* and Yu-Qiang Jiang

Key Laboratory of Conveyance and Equipment, Ministry of Education, East China Jiaotong University, Nanchang 330013, People’s Republic of China
* Author to whom any correspondence should be addressed.
E-mail: hzc@ecjtu.edu.cn

Keywords: self-piercing riveting, lap shear test, impact damage, residual strength, post-impact fatigue life

Abstract
The low-velocity impact behaviors of DP590/AA6061 self-piercing riveting (SPR) joints are studied at the impact energies of 5 J, 10 J, 20 J, 30 J, and room temperature (25 °C). The lap shear and fatigue tests, and the cross-sectional microscopies of joints are used to assess the mechanical property evolutions of the joints after low-velocity impact. The results show that the absorbed impact energies of SPR joints reach the critical value at an impact energy of 30 J, the exceeded impact energy causes crack failures in the sheets and decreases the interlocking performance of the joints. The static property and the absorbed energy of the SPR joints are reduced by 16% and 36% when the joints are impacted at 30 J, respectively. The low-velocity impacts do not change the failure forms of the joints, but significantly reduce the mechanical interlocking properties of the joints. The fatigue lives of the SPR joints are reduced due to low-velocity impact, and the impacted joints are more sensitive to cyclic loadings.

1. Introduction

Due to the development of lightweight materials and forming techniques, various lightweight materials are widely used in body structures to reduce weight, fuel consumption, and CO₂ emissions, such as ultrahigh strength steels, aluminum alloys, titanium alloy, and so on [1, 2]. Significant weight reduction through the extensive use of lightweight aluminum alloys and advanced high-strength steel materials has become the most important means of body-weight reduction [3]. The multi-material structure designs can significantly reduce the weight of the body structures, and represent the development trend of automobile body structures. The traditional join method of multi-material structure is bolt connection [4, 5]. Mechanical fasteners with bolt-nuts will inevitably encounter problems due to the uneven load distribution and stress concentration, such as loosening [6], reduced clamping force [7], and low fatigue strength [8]. Compared with conventional bolt-nut connection processes, self-piercing riveting (SPR) has the special advantages of no predrilling, fast forming speed, reliable connection, and high fatigue strength [9]. Therefore, the SPR is broadly used in the connections of different materials, especially for the connections between ultra-high-strength steel and aluminum alloys [10, 11].

During the SPR, the process parameters, such as the bottom die, sheet/rivet characteristics, have tremendous effects on the riveting characteristics of the SPR joints. Kim et al [12] reported the influences of bottom dies and rivet lengths on the riveting characteristics of SPR joints, and established a Johnson–Cook damage model to describe the SPR process. Mori et al [13] successfully connected ultra-high-strength steel and aluminum alloy by optimizing the die shapes. Jin et al [14] reported the influences of rivets and dies on the geometric features and tensile shear strengths of AA6061/DP590 SPR joints, and the optimal process parameters are required. He et al [15, 16] reported the effects of sheet materials and thicknesses on the fatigue and fretting characteristics of SPR joints by investigating the fatigue lives and fretting failure mechanisms. Wei et al [17] explored the fatigue failure behaviors of DP780/AA6061 SPR joints with different lap orders, and found that
aluminum alloys are inclined to fracture when served as lower plates, while the failure form is rivet fracture when the DP780 is the lower plate.

The SPR joints of the vehicle bodies are inevitably subjected to impact damages in the service process [18, 19]. For the car body structures, the impact damages mainly come from low-velocity impacts, such as the impact from slight scratching and collision, rain and hail attack, and road splashing small stones [20]. The low-velocity impact is also called large mass impact, and the impact velocity usually ranges from 1–10 m s$^{-1}$ in the low-velocity impacts [20, 21]. The drop-weight impact tests are widely used to assess the low-velocity impact damage behaviors of metals [22, 23], composites [24, 25] and metal composite laminate structures [26, 27]. Andréa et al [28] explored the impact resistance of AA2024-T3 alloy and carbon fiber reinforced polyphenylene (CFRP) sulfide joints using the low-velocity drop-weight impact tests at impact energies of 2 J to 8 J, and found that 6.5 J is the critical absorbed impact energy of the joints. Borba et al [29, 30] explored the impact damage and damage propagation sensitivity of CF-PEEK frictional riveted joints and bolted joints. Zhang et al [31] studied the energy absorption characteristics of CFRP plates with different fiber modulus under different impact angles, and found that the intra-laminar force behavior shows nonlinear relationships between impact angle and fiber modulus. Different from non-metallic materials, metal structures can absorb the impact energy through plastic deformation, and improve the critical absorbed impact energy [32, 33]. Khoramishad et al [34] investigated the effects of stacking sequences on low-velocity impact behaviors of metal laminates, and found that the impact properties of metal laminates are mainly affected by the volume fraction of metal layers, the material characteristics of the first and last metal layers, and the number of metal layers. Parnanen et al [35] reported that the steel’s surface conditions do not significantly influence the impact response and debonding between lower metal sheets and composite parts. Kosedag et al [36] studied the low-velocity impact behavior of B4C/Al6061 metal matrix composites by the drop-hammer impact tests, and found that the Al6061/B4C metal matrix composite materials exhibit the best impact property when the volume fraction of B4C is 15%.

However, there are few studies on the low-velocity impact behaviors of the SPR joints and the mechanical property evolutions of the joints after impact. In this work, the low-velocity impact behaviors of DP590/AA6061 SPR joints are studied. The mechanical properties of SPR joints after impact are tested, and the effects of impact damages on the mechanical properties and fatigue lives are analyzed.

### 2. Materials and methods

#### 2.1. Material and riveting process

The materials used in this work are 2 mm AA6061-T651 aluminum alloy plates and 1.5 mm DP590-A high strength steel plates. The chemical compositions of the plates are shown in table 1. The mechanical properties of DP590 steel and AA6061 aluminum alloy are listed in table 2.

| Material  | Yield strength (MPa) | Tensile strength (MPa) | Hardness (HRB) | Elongation (%) |
|-----------|----------------------|------------------------|----------------|----------------|
| AA6061    | 255                  | 290                    | 95             | 12             |
| DP590     | 380                  | 590                    | 162            | 20             |

The DP590 steel and AA6061 aluminum alloy were machined to the dimensions of 135 mm × 36 mm. Due to the better plastic deformation ability of DP590 steel, the DP590 high-strength steel was used as the upper plate, and AA6061 aluminum alloy was served as the lower plate in the SPR process. The lap length of the SPR joints is 36 mm, as shown in figure 1 [37].

To get a better forming quality, the semi-hollow boron steel rivets with a height of 6.5 mm and hardness of H4 were selected in the SPR process, and the boss die was used as the bottom die, as displayed in figures 2(a) and (b) [13, 14]. The RV300023 hand-held battery-driven SPR machine produced by Henrob Company was used for riveting. Figure 2(c) shows the cross-section of the typical riveted joint. It can be found from figure 2(c) that a
symmetrical SPR joint is obtained, and the remaining thickness of the aluminum lower plate is 0.502 mm, indicating the good mechanical interlock and stabilized riveting quality [38].

2.2. Low-velocity impact and mechanical tests

2.2.1. Drop-weight impact tests

According to ASTM E2298–15, the drop-weight impact tests were performed to investigate the impact resistance of riveted joints [39]. And the drop-weight impact tests were carried out at room temperature (25 °C) and humidity conditions using the CEAST 9340 drop-weight impact test system. Referring to the daily automobile service environments, the impacts of the body structures are mostly low-velocity impacts with energies less than 30 J [25]. Therefore, the impact energies of 0 J, 5 J, 10 J, 20 J, and 30 J were used in the drop-weight impact tests, and the impact tests were repeated five times at each energy level. In the impact tests, the impact velocities are less
than 10 m s\(^{-1}\), and the impact tests are regarded as low-velocity impact tests \([20, 21]\). During the impact tests, the punch with the same mass was fallen from different heights, and the required impact energies and velocities were obtained, as shown in Table 3.

Figure 3 shows the structures of fixture and punch. The fixture is composed of two adjustable rectangular hot-formed steel plates with a thickness of 9 mm, and the fixture is used to fix the SPR joints. The \(\Phi 30\) mm hole is machined to ensure that the rivet is only affected by the impact force during the test. The punch is aligned to the center of the riveted joint.

### 2.2.2. Static strength tests

To evaluate the residual quasi-static strengths of the post-impact SPR joints, the lap shear tests were performed using the MTS landmark dynamic materials testing system at a tensile rate of 2 mm min\(^{-1}\) and room temperature (25 °C) \([40]\). The lap shear tests at each impact energy level were replicated three times. To reduce the extra bending moment of the specimen in the test, the shims of 36 \(\times\) 36 \(\times\) 2 mm and 36 \(\times\) 36 \(\times\) 1.5 mm were clamped at the end of the specimen.

### 2.2.3. Fatigue testing

To evaluate the fatigue life of the post-impact SPR joints, the fatigue tests were carried out on QBG-50 high-frequency fatigue testing machine. The sine wave load was applied to the specimen at a frequency of 80 Hz. Four maximum stress levels (60%, 70%, 80%, and 90% of the maximum static strength) and a stress ratio of \(R = 0.1\) were adopted to determine the fatigue fitting (F-N) curves of the post-impacted SPR joints \([41]\). According to ASTM E739, four repeated tests were carried out at each impact energy and stress to ensure the accuracy of the fatigue fitting curve (F-N) of SPR joints \([42]\). In the fatigue tests, the complete joint failure was determined when macroscopic cracks appear, or static/dynamic loads exceed the set limits of the SPR joints, or the joints that can bear 10\(^6\) cycles are regarded as the conditions for the suspension of fatigue test.

### 3. Results and discussion

#### 3.1. Impact characteristics of the SPR joints

The drop-weight impact tests with different impact energies are executed to get the impact characteristics of the DP590-AA6061 SPR joints. Figure 4 shows the impact load-time and absorbed energy-time curves. The impact load-time curves at different impact energies present the same variation trends, i.e., the load increases quickly at the initial stage of the impact tests. Then, the impact loads are increased to the peak values slowly. Next, the
impact loads are decreased to zero gradually. Furthermore, the impact energies have obvious effects on the impact loads, as illustrated in figure 4. With the increase of impact energy, the impact loads increase, and a platform of impact loads appears when the impact energies exceed 10 J, as shown in figures 4(c)–(d). When the impact energies exceed 10 J, large impact velocities are obtained, and the peak load appears at a short time. On the other hand, the SPR joints are suffered from large deformation velocities at high impact energies, and the spring back of the punch is postponed. So, a platform of impact loads appears, as displayed in figures 4(c)–(d). With the increase of impact energy, the absorbed energies are increased to the peak values, and then decreased due to the spring back of the specimen.

Generally, the incipient damage point ($P_i$), the maximum load point ($P_m$), the failure point ($P_f$) and the total energy absorption point ($P_t$) are the characteristic points in figure 4. The impact loads and absorbed energies at these points indicate the abilities of the SPR joints to withstand deformation, damage and failure at different stages. The points of $P_i$, $U_i$ are used to describe the incipient damage point of joints, and are adopted to represent the capacity of a structure to bear the damage and deformation initiations [29, 43]. The maximum load point ($P_m$) indicates the occurrence of critical damage. The too-small $P_m$ value represents the low stiffness of the riveted joint, indicating that the damage occurs more easily in this case. $U_f$ is the maximum absorbed impact energy of the joint in the drop-weight impact test. The SPR joint can not bear the impact load when the impact energy exceeds $U_f$. $U_t$ is the total energy absorbed by the joint during the impact test. It can be found from figure 4 that with the increase of impact energy, the values of $P_i$, $P_m$ and $P_f$ are increased rapidly, indicating the strong damage resistance of the SPR joints. The time intervals between the $P_f$ and $P_t$ points are decreased with the increased impact energies, i.e., the time required to propagate the damages decreases with the increased impact energy, and the high-energy impact causes the earlier damage failure of the joints. To further analyze the impact characteristics of the SPR joints, the normalized absorbed-energies are listed in table 4.

$U_i/U$ is the normalized total energies absorbed by the joints in the impact tests. From table 4, the $U_i/U$ increases with the increase of impact energy ($U$). The absorbed energy $U_i$ is smaller than the impact energy ($U$). So, the spring back of the punch occurs, and the SPR joints are not penetrated by the punch. Generally, the
spring back is caused by the energy of U-Ut [43]. It can be found from figure 4 and table 4 that with the increase of impact energies, the values of U-Ut are increased, indicating the increased spring back of the SPR joints. Due to the strong spring back, the time intervals between Pf and Pt points are decreased at higher impact energies. So, the release of the absorbed energy is accelerated. The Ut-Um is the difference value between the absorbed energy (Ut) and the absorbed energy to maximum load (Um) of the joint, and this parameter stands for the energy that causes the failure of the joint. When the impact energies are increased from 5 J to 30 J, the values of Ut-Um are increased from 0.452 J to 2.554 J, indicating the increased damages of the SPR joints.

Figure 5 shows the failure forms of the impacted DP590/AA6061 SPR joints. The depressed deformations of the sheet metals are the typical impact deformation behaviors of the SPR joints [23]. As can be seen from figure 5 that the depressed deformations are the main deformation characteristics of the SPR joints. There are no obvious impact damages when the impact energies are lower than 5 J, as shown in figure 2(c) and figure 5(a). However, with the increase of impact energies, impact damages occur. When the impact energy is 10 J, a crack between the rivet and upper sheet is formed, as displayed in figure 5(b). With the further increase of impact energies, the rivet and sheets are separated, figure 5(c), indicating the accelerated impact damages and the

Table 4. The characteristic points and normalized energies at different impact energies.

| U(J) | 5       | 10      | 20      | 30      |
|------|---------|---------|---------|---------|
| P_(f) (kN) | 1.179 ± 0.070 | 1.769 ± 0.028 | 2.289 ± 0.040 | 3.260 ± 0.061 |
| U_(f) (J) | 0.050 ± 0.022 | 0.059 ± 0.026 | 0.072 ± 0.013 | 0.096 ± 0.017 |
| P_(m) (kN) | 6.450 ± 0.065 | 7.814 ± 0.131 | 8.924 ± 0.120 | 9.826 ± 0.104 |
| U_(m) (J) | 4.031 ± 0.101 | 7.598 ± 0.084 | 16.278 ± 0.121 | 24.588 ± 0.109 |
| P_(r) (kN) | 4.358 ± 0.117 | 5.687 ± 0.180 | 7.907 ± 0.102 | 8.080 ± 0.120 |
| U_(r) (J) | 5.218 ± 0.020 | 10.148 ± 0.026 | 20.042 ± 0.022 | 29.972 ± 0.019 |
| U_/U | 4.483 ± 0.057 | 8.739 ± 0.064 | 17.791 ± 0.103 | 27.142 ± 0.042 |
| U_-U_m/U | 0.888 ± 0.016 | 0.874 ± 0.011 | 0.890 ± 0.013 | 0.905 ± 0.014 |
| ΔU/U | 0.806 ± 0.020 | 0.756 ± 0.013 | 0.814 ± 0.011 | 0.820 ± 0.014 |
| U_-U_m | 0.112 ± 0.012 | 0.126 ± 0.014 | 0.110 ± 0.010 | 0.095 ± 0.015 |
| U_/U | 0.452 ± 0.134 | 1.143 ± 0.106 | 1.513 ± 0.192 | 2.554 ± 0.141 |
| U-U_t | 0.517 ± 0.053 | 1.261 ± 0.071 | 2.209 ± 0.103 | 2.858 ± 0.045 |

Figure 5. The failure forms of impacted joints at impact energies of (a) 5 J; (b) 10 J; (c) 20 J; (d) 30 J.
reduced mechanical interlocking properties of the joints. Furthermore, there are no cracks in the low sheets when the impact energies are less than 20 J, as illustrated in figures 5(a)–(c). The significant cracks occur in the low sheet when the impact energy is 30 J, as shown in figure 5(d). Meanwhile, the value of the maximum absorbed energy $U_f$ is 29.972 J when the impact energy is 30 J, which is close to the impact energy, and the joint is seriously damaged when compared with the joints at small impact energy. Therefore, it can be concluded that the maximum impact energy that the joint can withstand is about 30 J, and this is agreed with the normalized total energies absorbed by the joints, as listed in table 4.

When the impact energy exceeds 30 J, the specimens are penetrated, and the absorbed energies of the SPR joints convert to heat, internal energy, and other forms of energy. Figure 6 shows the morphologies of the bottom sheets in the SPR joints impacted at 40 J and 45 J. It is observed that cracks of different lengths are produced at the bottom sheets of the riveted joints. Therefore, the maximum energy without the penetration of joints is about 30 J-40 J.

3.2. Post-impact quasi-static mechanical strength

The shear load is one of the most common loads that the SPR joints are subjected to in actual service conditions. Figure 7 shows the mechanical strengths of impacted joints at different impact energies. In the load-displacement curves in figure 7(a), the load-displacement curves show similar variations, and the typical double-peaked features are presented. With the increase of impact energy, the plastic deformations are increased in the impact tests, and the mechanical interlocking properties are reduced. Therefore, the failure displacement and
peak load decrease gradually, indicating the increased impact damages of the SPR joints, as shown in figures 5 and 7(b). Besides, the max failure displacements decrease with the increased impact energy. From figure 7(b), the residual strengths are obtained. The residual strength is defined as the ratio of the static strength of impacted SPR joints with the static strength of un-impact SPR joints. The lap shear tests of joints are carried out three times to obtain the lap shear force of joints at different impact energies. The lap shear force of impacted joints at each impact energy is normalized by the average lap shear force of the non-impact joint, and then the residual strengths are obtained. A similar method is reported by Borba et al [29]. As shown in figure 7(b), the residual strengths are decreased with the increased impact energy, and the quasi-static strength of the joint is decreased 16% for the 30 J impacted joint, which indicates the increased impact damages.

Figure 8 shows the failure forms of joints at different impact energies. After the lap shear tests, the rivets are detached from the bottom aluminum alloy plates, and the impact has little effect on the failure forms of the SPR joints, as shown in figure 8. During the quasi-static shear tests, the foot of rivet is severed from the lower plate, and the first peak load occurs, as shown in figure 7(a). With the increased shear deformation, the rivet continues to disengage from the lower plate, and the rivet foot is hooked by the lower plate (figure 9, the area marked by No. 1), resulting in an increased load, and the second peak is formed, as displayed in figure 7(a). However, less plastic deformation is required to separate the rivet from the aluminum plate, (figure 9, the area marked by No. 2), and the second peak load is decreased when compared with that of the first peak, as shown in figure 7(a).

The energy absorption value of the joints in the lap shear test is an important parameter to evaluate the cushioning and shock absorption performance of the SPR joint [44]. The energy absorption value of a joint is expressed by the area enclosed by the load-displacement curve and the coordinate axes in figure 7(a). Figure 10 shows the energy absorption values of the post-impact joints at various impact energies. The energy absorption values of the joints are decreased by 0.9%, 8.7%, 20%, and 36% respectively after impact at 5 J, 10 J, 20 J, and 30 J.
It can be found from figure 10 and figure 7(b) that the SPR joints can bear a large shear load when the impact energy is below 10 J. However, the shear load resistance and the cushion absorption performance of the joint are significantly reduced after a 30 J impact, indicating the decreased reliability of the riveted joints. In this work, the high cycle fatigue tests of the joints are carried out to further discuss the reliability of the joints after impact.

3.3. Fatigue behavior of the impacted joints

According to the analysis in 3.1, the joints lose the excellent interlock performance, and can not sustain the shear loads at the failure point \( P_f \). Figure 11 shows the variations of \( U_f - U \) (the difference between the maximum absorbed impact energy \( U_f \) and the impact energy \( U \)). When the value of \( U_f \) is larger than \( U \), i.e., \( U_f - U > 0 \), the joints can absorb the impact energy well. Otherwise, the impact energy exceeds the maximum amount of impact energy that the joint can withstand. According to figure 11, the maximum impact energy that the joint can withstand is about 30 J. The cracks of the SPR joints impacted at 30 J energy in figure 5(d) also indicate the serious damages of the joints. Meanwhile, there is a significant decrease in the shear load resistance and cushion shock absorption performance of the joint subjected to the impact energy of 30 J, as displayed in figure 7(a). Therefore, the impacted joints with 30 J are selected to carry out the fatigue tests to examine the effect of impact damage on the fatigue life of riveted joints.
The post-impact high cycle fatigue tests are used to characterize the susceptibility of the joints to impact damage generations [45]. Figure 12 shows the F-N curves of the SPR joints at the impact energies of 0 J and 30 J. Due to the plastic deformation and damages in the impact tests, the interlock performance of SPR joints and static strength are significantly reduced after the impact at 30 J, as displayed in figures 5(d) and 7. Meanwhile, the slope of the F-N curve for joints subjected to impact energy of 30 J is larger than that of the um-impacted joints, indicating that the fatigue life of the impacted joints is more sensitive to fatigue load. When the SPR joints are impacted at 30 J, the diameter of the rivet hole is expanded due to the plastic deformation of the metal material, as shown in figures 5 and 9. Therefore, the rivet is more easily separated from the metal material, and the fatigue life is more sensitive to the fatigue load.

Figures 13–14 shows the fatigue failure forms of the joints before and after the impact, and the forms of fatigue failure both before and after the impact are the fractures of the lower aluminum plates. The bottom plates are fractured after the high-cycle fatigue tests, and the cracks are extended along the circumference of the rivet legs, as displayed in figure 13. The fracture micro-topographies in figure 13 are shown in figure 14. Figures 14(a), (c)
shows the microscopic morphologies of area 1 marked in figure 13, and figures 14(b), (d) shows the microscopic morphologies of area 2 in figure 13. The quasi-static and fatigue failure characteristics in figure 14 are typical failure characteristics of SPR joints under cyclic loading [17]. Meanwhile, the impact damages do not change the fatigue failure forms of the joints, although the fatigue life is reduced after impact damage, as illustrated in figure 12. However, the size of dimples and secondary cracks are increased when the SPR joints are impacted at 30 J. During the impact tests, the micro-voids and cracks are formed in the bottom sheets, and the micro-voids and cracks are easy to grow up in the fatigue tests, leading to the increased dimple sizes and secondary cracks, and the decreased strength and fatigue life, as shown in figures 14(c), (d). Figure 14(e) shows a significant plastic deformation in area 3 (figure 13), indicating that the initial damages are mainly caused by the impact, and the fatigue loading caused minor initial damage to the sheet metal. Figure 14(f) shows the cracks generated in the lower aluminum alloy plate due to shear loading in the fatigue test. The generation and growth of cracks in the lower plate are the main failure reasons of the fractured joints.
4. Conclusion

In this work, the effects of low-velocity impact on the mechanical properties and fatigue life of the SPR joints are investigated, and the main conclusions are following:

1. The absorbed impact energies of SPR joints reach the critical value at an impact energy of 30 J. The exceeded large impact energy causes the cracks in the sheets, and decreases the interlocking performance of the joints.
2. The static property of the SPR joint is reduced by 16%, and the absorbed energy is reduced by 36% when the joints are impacted at 30 J. The low-velocity impacts do not change the failure forms of the joints, but reduce the mechanical interlocking properties of the joints.
3. The fatigue lives of the SPR joints are reduced due to low-velocity impact, and the impacted joints are more sensitive to cyclic loading. The fatigue failure forms are ductile fracture and fatigue fracture.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (51875201).

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

ORCID iDs

Yi-Guang Zhao @ https://orcid.org/0000-0003-0300-9484
Zhi-Chao Huang @ https://orcid.org/0000-0001-6547-4678

References

[1] Kayode O and Akintalabi E 2019 An overview on joining of aluminium and magnesium alloys using friction stir welding (FSW) for automotive lightweight applications Mater. Res. Express 6 112005
[2] Jiang Y et al 2020 A new method to increase the spheroidization rate of lamellar α microstructure during hot deformation of a Ti-6Al-4V alloy Adv. Eng. Mater. 22 2000447
[3] Li Y et al 2012 Light weighting of car body and its challenges to joining technologies Journal of Mechanical Engineering 48 44–54
[4] Ahn B 2021 Recent advances in brazing fillers for joining of dissimilar materials Metall. 11 1037
[5] Redmann A et al 2021 Evaluation of single-lap and block shear test methods in adhesively bonded composite joints Journal Composite Science 5 27
[6] Yang S et al 2016 Loosening analysis for fastening screw of automotive door trim parts Int. J. Automot. Technol. 17 671–9
[7] Liu Z et al 2021 Experimental study on performance characterization of bolted joint under transverse loading Measurement 182 109698
[8] Li L et al 2021 Deterioration of fatigue strength of bolted connection plates under combined corrosion and fatigue J. Constr. Steel Res. 179 106559
[9] Huang Z et al 2017 Developing a self-piercing riveting with flange pipe rivet riveting aluminum sheets Int. J. Adv. Manuf. Technol. 91 2315–28
[10] Meschut G, Janzen V and Offermann T 2014 Innovative and highly productive joining technologies for multi-material lightweight car body structures J. Mater. Eng. Perform. 23 1515–23
[11] Jia Y et al 2021 Forming quality and fatigue behavior of self-piercing riveted joints of DP590 and AA6061 plates Adv. Mater. Sci. Eng. 2021 1–10
[12] Kim C et al 2021 Development of analytical strength estimator for self-piercing rivet joints through observation of finite element simulations Int. J. Mech. Sci. 202-203 106499
[13] Mori K et al 2006 Plastic joining of ultra high strength steel and aluminium alloy sheets by self piercing rivet CIRP Annals-Manufacturing Technology 55 283–6
[14] Jin X et al 2011 Process optimization of self-piercing riveting aluminum to high strength steel using DOE method Chinese Journal of Automotive Engineering 1 185–91
[15] Zhang X et al 2020 Fatigue characterization and crack propagation mechanism of self-piercing riveted joints in titanium plates Int. J. Fatigue 134 105465
[16] Zhao L et al 2015 Influence of sheet thickness on fatigue behavior and fretting of self-piercing riveted joints in aluminum alloy 5052 Mater. Des. 87 1010–7
[17] Wei W et al 2020 Characteristics of fretting damage in hybrid DP780/AA6061 self-piercing riveted joints Journal of Mechanical Engineering 56 169
[18] Cheng X et al 2018 Effects of stacking sequence and rotation angle of patch on low velocity impact performance of scarf repaired laminates Composites Part B 133 78–85
[19] Khashaba U A and Othman R 2017 Low-velocity impact of woven CFRE composites under different temperature levels Int. J. Impact Eng. 108 191–204
[20] Sjoblom P O, Hartness J T and Cordell T M 1988 On low-velocity impact testing of composite materials J. Compos. Mater. 22 30–52

[21] Shivakumar K N, Elber W and Illg W 1985 Prediction of low-velocity impact damage in thin circular laminates AIAA J. 23 442–9

[22] Huang Z et al 2020 Low speed impact properties of 5052 aluminum alloy plate Procedia Manufacturing 50 668–72

[23] Ma Y, Hu H and Xiong X 2014 Comparison of damage in FMLs, aluminium and composite subjected to low-velocity impact Acta Aeronautica et Astronautica Sinica 35 1902–11

[24] Wang C et al 2021 Low-velocity impact response of 3D woven hybrid epoxy composites with carbon and heterocyclic aramid fibres Polym. Test. 101 107314

[25] Dong Y and Zhu C 2008 Drop hammer impact response and energy absorption capacity of carbon-polyester hybrid composite plates Proc. of the Int. Conf. on Advanced Textile Materials & Manufacturing Technology 2018 297–300

[26] Soroush A, Sajjad F N and Fathollahi T B 2021 An experimental and numerical investigation on low velocity impact response of GLAREs Compos. Struct. 271 114123

[27] Kader M A et al 2021 Strain-rate dependency and impact dynamics of closed-cell aluminium foams Materials Science & Engineering A 818 141379

[28] Andrá N M, Santosa J F and Sergio T A F 2020 Impact resistance of metal-composite hybrid joints produced by frictional heat Compos. Struct. 233 111754

[29] Borba N Z et al 2020 Low-velocity impact response of friction riveted joints for aircraft application Mater. Des. 186 108369

[30] Borba N Z et al 2020 Mechanical integrity of friction-riveted joints for aircraft applications Compos. Struct. 232 111542

[31] Zhang J, Li Z and Zhang Q 2019 Study of fiber modulus effect on impact energy absorption characteristics of composite laminates at normal and oblique impacts Mater. Res. Express 6 085610

[32] Tsotsis T K 2012 Considerations of failure mechanisms in polymer matrix composites in the design of aerospace structures Failure Mechanisms in Polymer Matrix Composites 2012 227–78

[33] Davies G A O and Zhang X 1995 Impact damage prediction in carbon composite structures Int. J. Impact Eng. 16 149–70

[34] Khoramishad H, To Tsotsis T K 2012 Considerations of failure mechanisms in polymer matrix composites in the design of aerospace structures Failure Mechanisms in Polymer Matrix Composites 2012 227–78

[35] Kosedag E and Ekici R 2019 Low-velocity impact performance of B4C particle-reinforced Al 6061 metal matrix composites Mater. Res. Express 6 126556

[36] Hsiao Y H et al 2022 Influence of edge distance on quality and static behaviour of self-piercing riveted aluminium joints Mater. Des. 207 111542

[37] Li D et al 2022 Influence of edge distance on quality and static behaviour of self-piercing riveted aluminium joints Mater. Des. 207 111542

[38] ASTM E2298–15 2015 Standard test method for instrumented impact testing of metallic materials (West Conshohocken, PA: ASTM International)

[39] ASTM E1002-10 2010 Standard test method for apparent shear strength of single-lap joint adhesively bonded metal specimens by tension loading (metal to metal) (West Conshohocken, PA: ASTM International)

[40] Huang Z, Jia Y and Lai J 2021 Fatigue characteristics and failure mechanism of self-piercing riveted joints of DP590 and AA6061 plates Forming the Future, The Minerals, Metals & Materials Series 1423–36

[41] ASTM 2015 E739-10 Standard practice for statistical analysis of linear or linearized stress-life (West Conshohocken, PA: ASTM International)

[42] ASTM 2015 E1651-12 Standard test method for determination of low-velocity impact energy absorption characteristics of composite laminates Int. J. Fatigue 45 263–72

[43] Ghaseminejad M N and Parvizi-Majidi A 1990 Impact behaviour and damage tolerance of woven carbon fibre-reinforced thermoplastic composites Construction & Building Materials 4 194–207

[44] He X et al 2014 Investigations of strength and energy absorption of clinched joints Comput. Mater. Sci. 94 58–65

[45] Melin L G, Sch J and Nyman T 2002 Fatigue testing and buckling characteristics of impacted composite specimens Int. J. Fatigue 24 263–72