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Recent development in finite element analysis of self-piercing riveted joints

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Abstract Self-piercing riveting (SPR) is a high-speed mechanical fastening technique which is suitable for point-joining advanced lightweight sheet materials that are dissimilar, coated, and hard to weld. Major advances have been made in recent years in SPR technique. Latest literature relating to finite element analysis (FEA) of SPR joints is reviewed in this paper. The recent development in FEA of SPR joints are described with particular reference to three major factors that influence the success of SPR technique: SPR process, failure mechanism, and mechanical behavior of SPR joints. The main FE methods used in FEA of SPR joints are discussed and illustrated with brief case studies from the literature. Areas where further useful progress can be made are also identified.

Keywords: Self-piercing riveting . Finite element analysis . Process monitoring . Failure mechanics . Mechanical properties

1 Introduction

Self-piercing riveting (SPR) is a cold-forming operation used to fasten two or more sheets of material by driving a semi-tubular rivet through the top sheet(s), piercing the bottom sheet, and spreading the rivet skirt under the guidance of a suitable die. As the process relies on a mechanical interlock rather than fusion, it can be used for a wide range of advanced materials that are dissimilar, coated, and hard to weld [1]. The principle of SPR is given in Fig. 1 [2]. Some general information on the SPR is available from Henrob [3], Bollhoff [4], Emhart [5], and TWI [6]. The SPR technique developed rapidly in recent years [7– 9]. Fratini and Ruisi [10] investigated the SPR for aluminum alloys-composites hybrid joints. Durandet et al. [11] studied the laser-assisted SPR of AZ31 magnesium alloy strips. Chenot et al. [12, 13] discussed some important numerical issues in metal-forming process, including meshing, remeshing and adaptivity, and parallel computing and coupling between work-piece and tools. Pickin et al. [14] reported the results from an investigation into the joining of lightweight sandwich sheets to aluminum using the SPR. Johnson et al. [15] proposed an online monitoring method of the SPR process to provide non-destructive testing of the mechanical interlock. Han et al. [16] reported a comparison of the mechanical behavior of SPR and resistance spot-welded joints under different loading conditions. Matsumura et al. [17] investigated dissimilar metal joint technology with the SPR to join aluminum alloyed roof panel with steel body. The complex joint geometry and its three dimensional nature combine to increase the difficulty of obtaining an overall system of governing equations for predicting the properties of the SPR joints. Finite element analyses (FEA) have been performed to achieve a deep understanding of the technique [18]. Latest literature relating to FEA of SPR joints is reviewed in this paper, in terms of SPR process, failure mechanism, and mechanical characteristics of the SPR joints.

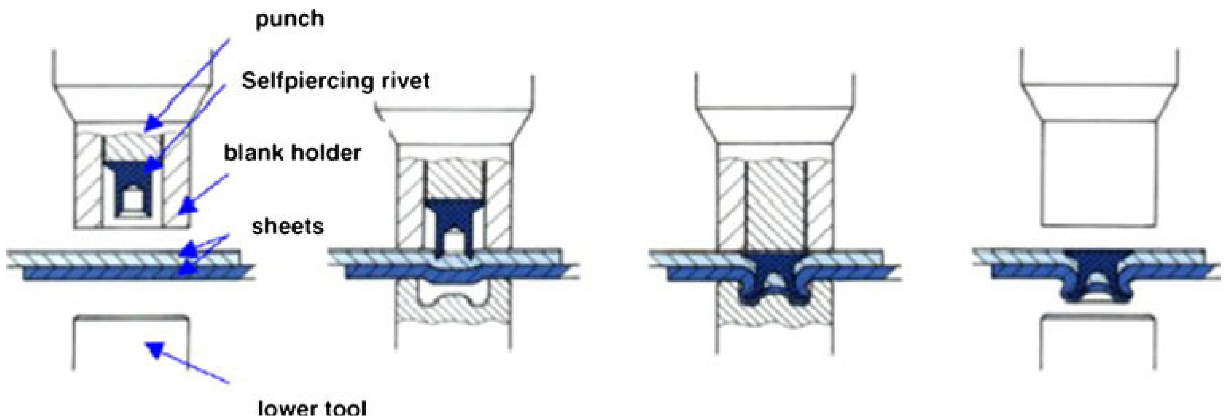

Fig. 1 Principle of self-piercing riveting [2]

2 SPR process

Due to the complicacy of the SPR process, it is very difficult to get insight into the joint during forming process. The effective way to analyze SPR joint during forming process is to perform numerical simulation. Several numerical techniques and different FEA software already allows the simulation of the SPR process. Mori et al. [19, 20] developed an SPR process for joining ultra-high-strength steel and aluminum alloy sheets. To attain better joining quality, the die shape was optimized by means of the finite-element (FE) simulation without changing mechanical properties of the rivet. Authors reported that the joint strength is greatly influenced by not only the strength of the sheets and rivets but also the ratio of the thickness of the lower sheet to the total thickness. Abe et al. [21] investigated the effects of the flow stress of the highstrength steel sheets and the combination of the sheets on the joinability of the sheets by FE simulation and an experiment. They found that as the tensile strength of the high-strength steel sheet increases, the interlock for the upper high-strength steel sheet increases due to the increase in flaring during the driving through the upper sheet, whereas that for the lower high-strength steel sheet decreases.

A 3D model was created by Atzeni et al. [22] in ABAQUS Explicit 6.4 and both the SPR process and the shear tests were simulated to take into account the strain and residual stress of the SPR joints. Comparisons with experimental results had shown good agreement, both in terms of deformed geometry and force-displacement curves. In a recent study, the same authors [23] presented a FE model for the analysis of the SPR processes. Correct model parameters were identified and numerical model validated in 2D simulations. In order to verify the capabilities of the software to predict joint resistance for given geometry and material properties, a 3D model was set up to generate a joint numerical model for simulating shearing tests.

It is well kwon that strain hardening must be considered when analyzing large plastic deformation. Xu [24] employed a nonlinear model to simulate the SPR process for examining the physical attributes of SPR joints. The four-noded quadrilateral 2-D element was used in the numerical analysis and the remeshing element was set when element distortions were large. Based on a combination of numerical and experimental investigations, Haberkorn et al. [25] described an approach which starts with the SPR process simulation and ends in a manageable full car model. Casalino et al. [26] proposed equations for governing the onset and propagation of crack, the plastic deformation, the space discretization, the time integration, and the contact evolution during the SPR process. A case study of the SPR of two sheets of the 6060T4 aluminum alloy with a steel rivet was performed using the LS-DYNA FE code. Some numerical problems entangled with the model setup and running were resolved and good agreement with experimental results was found in terms of joint cross-sectional shape and force–displacement curve. In Porcaro et al's study [27], an LS-DYNA 2D axisymmetric SPR model was validated against experimental results and the results from the riveting process simulation were used to generate a 3D numerical model of the riveted connection. A plastic FE model was employed by Liu et al. [28] to simulate the deformation features of semi-tubular rivet and sheets in SPR process. Both the simulation and the test results shown that the plastic deformation were mainly in the contacting area between rivet end and sheets.

Using DEFORM-2D software, Huang et al. [29] carried out an FE analysis of SPR process. The influence of raised altitude of concave die and rivet material on riveted joint performance was investigated. The results show that increasing raised altitude of concave die can enhance selflocking performance of riveted joint in certain scope. In another study [30], the SPR process with flat-bottom die joining 2A12 aluminum sheet and 08F steel sheet was simulated numerically in the same software. The authors reported that the stress and strain mainly concentrated in the region where the rivet contacts with the sheets, and the maximum stress was located in the rivet shank. Qu and Deng [31] presented a 2D axisymmetric FE model to predict the magnitude and distribution of deformation associated with the SPR process. In the study, the flow stress of the work-material was taken as a function of strain, strain rate, and temperature. The shape of the rivet joint and the stress, strain, and damage in both of the rivet and substrates were determined. Luo et al. [32] investigated the influence of die-rivet volume ratio on the SPR joints of Alto- steel and steel-to-Al combinations. The experimental results show that both of Al-to-steel and steel-to-Al combinations have large undercut when die-rivet volume ratio is greater than 1.

In Cacko et al's papers [33, 34], initial trials carried out to optimize the SPR process using special algorithms implemented into commercial FEA codes were presented. The optimization of the FEA model referred to both real shapes of a joint and force history. The authors found that these two facts are crucial at the beginning of implementation of more sophisticated model taking into account complex stress state in the joint and relation with material separation. The numerical modeling of the SPR joint was verified by experimental stack-up. In another study, Cacko [35] presented a review of selected material separation criteria available in commercial MSC software applied for the SPR process simulation.

The SPR technique is mainly applied to joining of two sheets. Preliminary research work has been made on multi-layer sheets SPR. In Kato et al.'s paper [36], an SPR process of three aluminum alloy sheets was simulated using LS-DYNA to find joinable conditions. In addition, the cross-tension test was also simulated by FEA to evaluate the joint strength. Abe et al. [37] investigated the joinability of the SPR process of three high-strength steel and aluminum alloy sheets. To improve the joinability with the high-strength steel sheets, the shape of the die was optimized by controlling the deforming behaviors of the sheets and rivet by means of the FE simulation. Huang et al. [38] carried out numerical simulation and experiment of multi-layer aluminum sheets SPR. The test results had shown that the transition point of the coneshaped head of the solid rivet, the size and position of groove affect directly the quality of the joints. The fillet at the transition point of the cone-shaped head of the solid rivet can decline the maximum stress of the rivet. Using Forge2005® FE software, Bouchard et al. [2] modeled large deformation of elastic–plastic materials for 2D and 3D configurations. They found that it is possible to export the mechanical fields of a 2D simulation onto a 3D mesh using an interpolation technique, and then to perform a 3D shearing test on the riveted structure. They also found that the mechanical history of the rivet/sheet assembly undergone during the SPR process plays a significant role in the numerical prediction of the final strength of the assembly. In order to evaluate the software robustness, numerical simulation of the SPR process was performed on three 1-mm-thick aluminum and steel sheets. Figure 2 shows the four different stages of the SPR of three sheets.

The SPR process currently utilizes high-strength steel rivets. The combination between steel rivets with an aluminum car body not only makes recycling time consuming and costly, but also galvanic corrosion. Galvanic corrosion occurs when dissimilar, conductive materials are joined and the ingress of water forms an electrolytic cell. In this type of corrosion, the material is uniformly corroded as the anodic and cathodic regions moves and reverses from time to time [1]. Abe et al. [39] investigated the joinability of aluminum alloy sheets by aluminum self-pierce rivets. To pierce the upper sheet, the diameter and edge angle of the rivet were modified. The shape of the die was also designed from trial and error using FEA. The effectiveness of the designed rivet die was evaluated from an experiment. Hoang et al. [40] investigated the possibility of replacing steel self-piercing rivets with aluminum ones, when using a conventional die in accordance with the Boellhoff standards. An experimental program was carried out. The test results were exploited in terms of the riveting force–displacement curves and crosssectional geometries of the riveted joints. The test data were also used to validate a 2D-axisymmetric FE model. The mechanical behavior of a riveted connection using an aluminum rivet under quasi-static loading conditions was experimentally studied and compared with corresponding tests using a steel rivet.

3 Failure mechanism

Although the SPR structures have been used in deferent industrial fields, especially in the automotive industry, there is still a lack of analytical description of mechanism of failure of the SPR structures. Numerical simulation may provide a means to overcoming these problems. Abe et al. [41] evaluated the SPR joinability of aluminum alloy and mild steel sheets through FE simulations and experiments. Defects in the riveting were categorized into the penetration through the lower sheet, the necking of the lower sheet, and the separation of sheets to obtain optimum joining conditions. Figure 3 shows the defects in the SPR joints. The results had shown that the SPR joinability for the upper steel sheet–lower aluminum sheet combination is better than that of the reverse combination. Eckstein et al. [42] characterized possible types of failure in the SPR structures. The paper differentiated four main fracture patterns in the joints. FE calculations were carried out using the program MSC Superform 2005 Release 3 with axisymmetric simplification for 2D analysis. It illustrated mechanical material investigations and simulations of fracture according to a micro-mechanical model of Rousselier.

A model was created by Dannbauer et al. [43] which accounts for a correct local stiffness and enables lifetime assessments of SPR joints. Test results from various specimen types covering parameter variations of material type, sheet thickness, rivet diameter, and others were used in the model. The result is a substitution model similar to that applied to spot welding but by consideration of additional parameters to achieve a good agreement with the experiments.

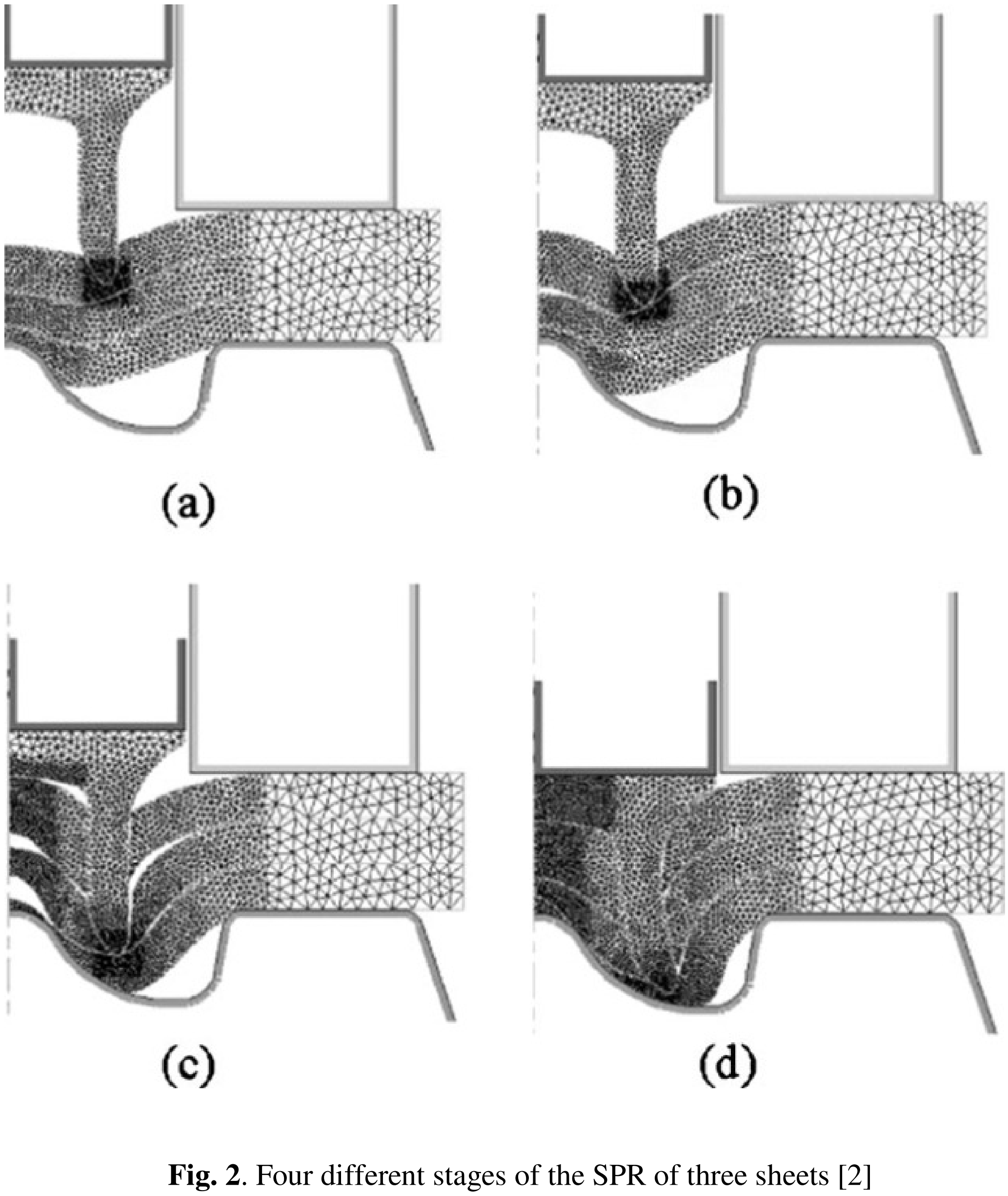

Fig. 2. Four different stages of the SPR of three sheets [2]

Porcaro et al. [44] carried out an experimental and numerical study on the behavior of SPR joints in aluminum alloy AA6060 under quasi-static loading conditions. Factorial design was used in the planning of the experimental program and in the interpretation of results. A 3D model was generated using explicit FE code LS-DYNA and used to compute the force failure envelope in the specimen reference system as well as in the rivet reference system.

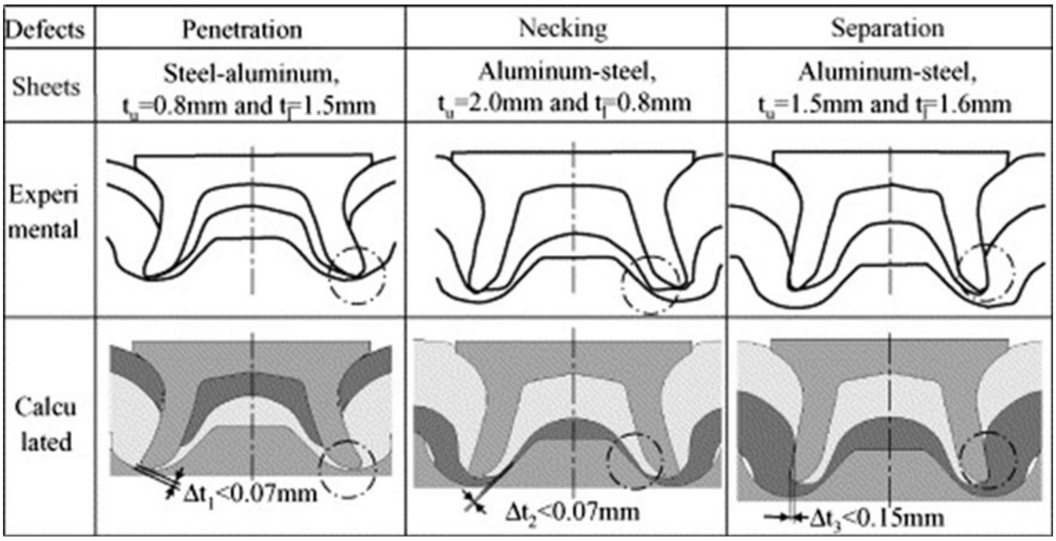

Fig. 3. Defects in the SPR joints [41]

4 Mechanical behavior of SPR joints

Joints are often the structural weakest points of a mechanical system when considering strength. Consequently, a considerable amount of numerical studies has been carried out on the mechanical behavior of SPR joints. Research in this area has shown that SPR gives joints of comparable static strength and superior dynamic behavior. For efficient simulations of stiffness and operational strength behavior, a node-independent SPR model was developed by Ruprechter et al. [45]. Global and local stiffness were modeled in a proper way and it is possible to determine the local stresses needed for the fatigue life estimation. The simulation results were verified with experimental results. In research paper of Galtier and Duchet [46], the main parameters that influence the fatigue behavior of sheet material assemblies were presented and some comparisons were made within sheet material joining techniques. It was found that the SPR joint fatigue strength mainly depends on the grade and thickness of the sheet placed on the punch side. In Lim's research paper [47], the simulations of various SPR specimens (coach-peel specimen, cross-tension specimen, tensile-shear specimen, pureshear specimen) were performed to predict the fatigue life of SPR connections under different shape combinations. FE models of various SPR specimens were developed using a FEMFAT SPOT SPR pre-processor.

The SPR process needs a large setting force. This large setting force can cause severe joint distortion and this will affect the assembly dimensions. It was suggested that the inclusion of the SPR joint distortion is generally needed for accurate global assembly predictions. In Huang et al's paper [48], a nonlinear FE model was built to study the joint distortion of SPR under different clamping force, blankholder diameter, and sheet size. The analysis results show that the clamping force and blankholder diameter are two important factors for the joint distortion while the sheet size has only minor effect. From the study, the relations of maximum joint distortion with clamping force, blankholder diameter, and sheet size were obtained, based on which the appropriate process parameters could be found to control the SPR joint distortion. Sui et al. [49] has built a FE model for simulating SPR process of 1.15 mm AA6016T4+1.5 mm AA5182O sheets. The results show that punching load was significantly affected by the deformation of rivet shank and the distortion of the joints was mainly affected by the binder force and the blankholder diameter.

The structural behavior of the SPR joints under static and dynamic loading conditions and how they are modeled in large-scale crash analyses are crucial to the design of the overall structure. Therefore, there is a need to perform dynamic testing on elementary joints in order to study its dynamic behavior. Porcaro et al. [50] investigated the SPR connections under quasi-static and dynamic loading conditions. Two new specimen geometries with a single rivet were designed in order to study the riveted connections under pull-out and shear impact loading conditions using a viscoelastic split Hopkinson pressure bar. 3D numerical simulations of the SPR connections were performed using the explicit FE code LS-DYNA. Static and dynamic tests were simulated using a simplified model that included only the specimen and the clamping blocks that connected the specimen to the bars. Figure 4 shows the 3D FE model of the test setup.

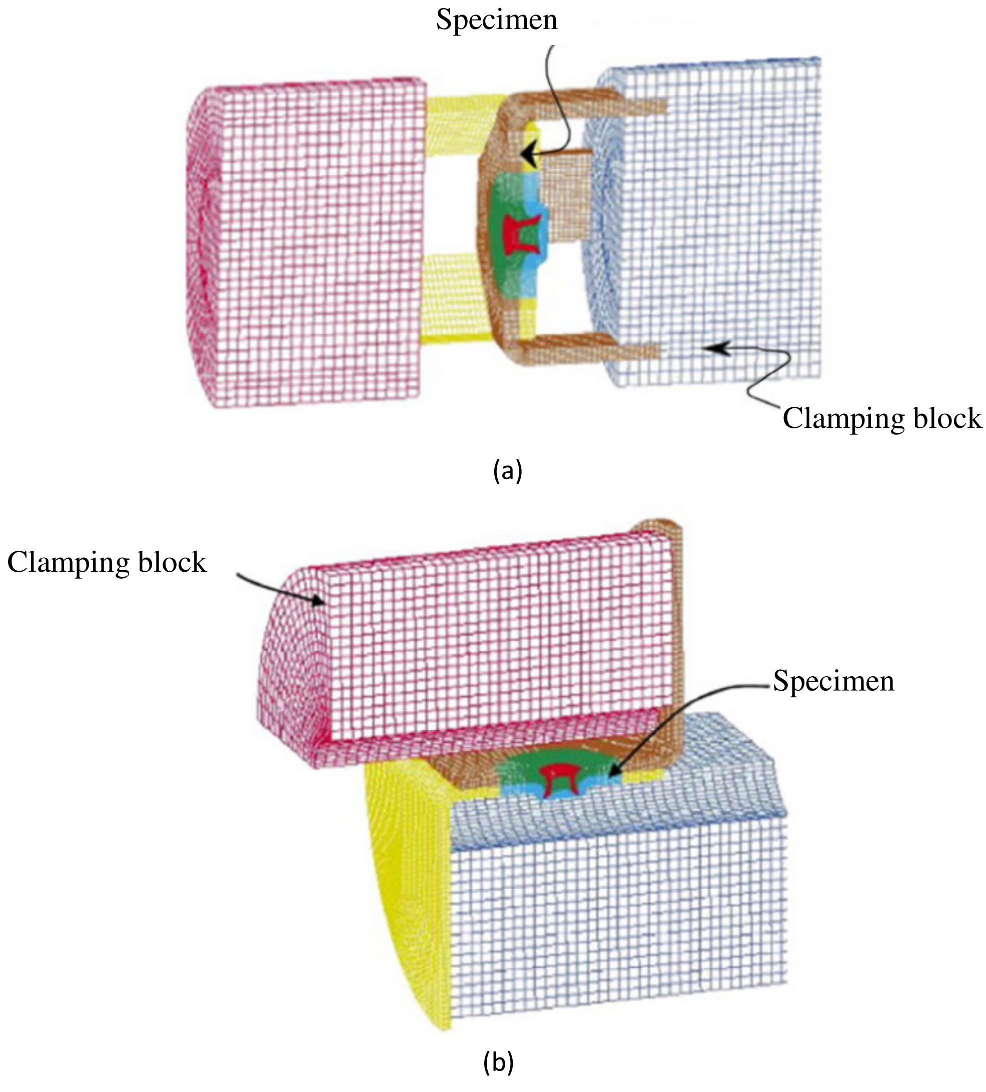

Fig. 4. 3D models of the test setup: (a) pull-out; (b) shear. [50]

It is believed that the SPR joints act to augment mechanical system damping capacity. In the present author's studies [51–53], free vibration characteristics of single lap-jointed cantilevered SPR beams were investigated theoretically using the 3D FEA. Numerical examples were provided to show the influence on the natural frequencies and natural frequency ratios of these beams caused by variations in the material properties of the substrate materials. Recent work by the present author and coworkers investigated in detail the free transverse vibration characteristics of single lap-joint SPR-bonded hybrid joints [54, 55]. The focus of the analysis was to reveal the influence on the transverse natural frequencies and mode shapes of the hybrid SPR joint of different characteristics of structural adhesives which encompass the entire spectrum of viscoelastic behavior ranging from the rubbery region to the rubber-to-glass transition region, then to the glassy region. It was found that the adhesive strength has a significant effect on odd mode shapes. When the adhesive is relatively soft, the mode shape at the lap joint is more pointed. But when the adhesive is relatively very stiff, the mode shape at the lap joint is fairly flat and there is a corresponding local stiffening effect. The consequence of this is that higher stresses will be developed in the stiffer adhesive than in the softer adhesive.

5 Summary

The SPR technique has become an increasingly popular mechanical joining method due to the growing use of alternative materials which are difficult or impossible to weld. Though it has been performed to achieve a deep understanding of the technique, the FEA of the SPR is still in its development phase. A literature survey on the FEA of the SPR technique has shown a limited number of relevant articles. In this paper, the research and progress in FEA of the SPR are critically reviewed from different perspectives, including process monitoring, process optimization, multilayer sheets riveting, aluminum rivet, fracture pattern, fatigue behavior, joint distortion, dynamic behavior, free vibration characteristics. To fully understand the behavior of the SPR, the FE model must include all the information from the riveting process and failure simulation. Thus there is also a requirement to determine the complex relationships between materials, SPR processes, and joint defects for the mechanical joint properties for both the static and dynamic cases. In other words, accurate, and reliable modeling of the SPR joint is still a very difficult task. The main goal of the paper is to review the latest literature relating to FEA of the SPR joints and to provide a basis for further research.

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