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Material parameter modeling and solution technique using birth–death element for notched metallic panel repaired with bonded composite patch

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Abstract This paper seeks to outline a novel three-layer model and a new birth–death element solution technique to evaluate static strength of notched metallic panel repaired with bonded composite patch and to optimize material parameters. The higher order 3D, 8-node isotropic solid element and 8-node anisotropic layered solid element with three degrees of freedom per node are respectively implemented to model substrate panel, adhesive layer and composite patch to establish three-layer model of repaired panel. The new solving technique based on birth–death element is developed to allow solution of the stress pattern of repaired panel for identifying failure mode. The new model and its solution are used to model failure mode and residual strength of repaired panel, and the obtained results have a good agreement with the experimental findings. Finally, the influences of material parameter of adhesive layer and composite patch on the residual strength of repaired panel are investigated for optimizing material properties to meet operational and environmental constraints.

1. Introduction

The repair for notched metallic structure with adhesively bonded composite patch holds superiority over that with mechanical riveting or fastening in terms of mechanical properties and efficiency, e.g., better geometry flexibility, lighter weight, higher stiffness and strength, improved durability, lower repair time and cost, etc.[1–3] Thus, adhesively bonded composite patch repairs to notched metallic substrate structure have received increasingly attention, and static and fatigue strengths of repaired metallic panels with the thin (less than 12.7 mm) and thick (more than 12.7 mm) thickness have been widely investigated.[4] Generally, thin panels were analyzed by using 2-D models,[5–13] whereas thick panels were done as a 3-D problem.[14–24] With thin panels, Naboulsi and Mall[5] proposed a 2-D model for the analysis of adhesive layer, composite patch and thin notched substrate panel. Sun and Klug[6] developed an effective spring model of adhesive layer from the Mindlin plate theory. Rao et al.[7] conducted the experiments to determine the residual bonding strength of repaired panel with three types of surface treatment subjected to cyclic

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loading. Hosseini-Toudeshky et al.[8] performed experimentally investigation on the influence of layer number of composites patch on crack growth life of single-sided repaired panels. Sabelkin et al.[9] carried out tests to investigate the effect of the stiffener on fatigue lives for both panels with and without adhesively bonded composite patch repair. Xiong and Shenoi[10] investigated experimentally the effects of patch thicknesses and fibre/epoxy prepreg materials on static and fatigue strengths of notched panels repaired with adhesively bonded composite patch. Okafor et al.[11] presented 2-D FE (finite element) model to simulate stress pattern of asymmetrically repaired panel with a central notch. Oterkus[12] and Tsamasphyros et al.[13] took notched substrate panel, composite patch and adhesive layer as individual layers and adhesive layer was regarded as continuous elastomer to establish 2-D two-layer model for calculating stress intensity factor at crackle tip of repaired panel. Ouinas[14] considered notched substrate plate and adhesive layer as continuous elastomers and composite patch as orthotropic elastomer to simulate crack propagation process by means of 2-D two-layer model and J-integration criterion.

Regarding thick panels, because of asymmetric repair to the panels, bending effects have been ignored in experimental investigations.[15] Klug and Sun[16] undertook edge crack propagation tests around central notch of thick panel. Jones and Chiu[17] achieved experimental investigation and numerical analysis on notch repair for thick structures. Due to the difficulty for allowing analytical solution of adhesively bonded composite patch repairs, numerical analysis based on FE and BE (boundary element) models were implemented to simulate stress fields and to evaluate the repair efficiency. Schubbe and Mall[18,19] established three-layer FE model from the 2-D Mindlin-plate element for simulating crack growth in thick panel repaired with bonded composite patch. Though the 3-D FE analysis has been employed to calculate stress intensity factors at the tip of a crack in repaired panels, no numerical analysis has been conducted to simulate crack growth process.[20–23] A combination of BE model and FE method (BEM/FEM) has been presented by Sekine et al.[24] to determine stress intensity factor. Oudad et al.[25] investigated the influences of mechanical properties of adhesive layer and composite patch as well as crack depth on plastic zone size of crack tip in by using 3-D non-linear FEA. It was showed that composite patch resulted to a significant decreasing of plastic zone size of crack tip.

In reality, optimization design on metallic panel repaired with bonded composite patch has received considerable attention recently. Mathias et al.[26] implemented genetic algorithms (GAs) to optimize bonding orientation and stacking sequence of composite patch to reduce stress pattern in repaired structure. Roberto[27] presented optimum design scheme for composite bonding repair by using genetic algorithm and found a significant influence of geometry of composite patch on fracture and fatigue lives of repaired panel. Breitzman et al.[28] conducted optimization design on the thickness and stacking sequence of composite repair patch under tensile loading by checking von Mises stress pattern. Ramji et al.[29] performed geometry optimization of notched panel repaired with bonded symmetrical composite patches with circle, rectangle, square, ellipse, octagon and expanded octagon shapes based on 3-D FEA.

With rapid growth of notched panel repaired with bonded composite patches, an elaborate study on the influences of important parameters such as patch thickness, layer angles and patch material, etc. on the mechanical behavior of repaired parts is urgently needed, because it could provide important information as a basis for technologists to decide what method is the best choice. However, there seems to be precious few works done on this subject; from the above review, most of researchers centered their attention upon the study on individual special issues of each parameter rather than on a comprehensive analysis of important parameters of adhesive layer and composite patch as a whole.[30] The paper, therefore, aims to present new three-layer FE model and a novel solution technique using birth–death element to solve the stress pattern for identifying failure mode of repaired panel and for investigating and comparing the influences of important parameters on the residual strength of the repaired panel.

2. Modified three-layer model and solution algorithm

Notched metallic panels repaired with adhesively bonded composite patch were fabricated to determine static mechanical properties and Fig. 1 shows the geometry and dimensions of repaired panels. The materials of substrate panel, adhesive layer and composite patch were the LY12 aluminum-alloy, SY-24C adhesive system and symmetric T300/3234 prepreg tape respectively. The panels with 350 mm length, 60 mm width and 2.4 mm thickness were manufactured from the substrates of LY12 aluminum-alloy and an edge-notch with 1.4 mm depth and 40 mm diameter was machined through linear cutting and polishing at the side of the panel for modelling corrosion pit. Surface treatment of substrate panel was made through acetone-cleaning and drying prior to adhesive bonding of composite patches. All patches are of rectangular shape. Since patch debonding occurs due to the development of high peel stress at the extremities of the load transfer regions (e.g., at the overlap end), in order to minimize the peel stress, a tapering was made along the longitudinal edge of patch by using plies of decreasing lengths from the bonded surface to the top with a cover ply, as is usually done in the actual applications. The taper of all patches had a constant nominal length with the uniform ply drop-off dependent on the number of plies. The composite single-sided patches were adhesively bonded to the notched panels. All the repaired specimens were cured at 160 °C for 2 h and then at 200 °C for 1 h. All specimen shoulders were adhesively bonded with ‘staircase’ aluminum-alloy tabs for suppressing the effect of tester grippers and for minimizing stress concentrations at the shoulders roots in the specimens (shown in Fig. 1). Static tensile tests of identical repaired specimens were conducted on MTS880-500 kN servo-hydraulic tester to determine the residual strength at room moisture and temperature as well as at a loading rate of 0.5 mm/min. In this context, the residual strength is defined as the ultimate load of the notched specimen repaired with adhesively bonded composite patch. The P–D (load–displacement) curves of tested specimens were recorded by tester. Fig. 2 shows that all the P–D curves of tested specimens appear almost identical in linear elastic scale. An existence of one peak on all P–D curve marks the debonding of adhesive resin at the interface between substrate panel and composite patch around the notch of repaired specimen, which results in a load-drop on the *P–D* curve. From the experimental observation, it is clear that all tested specimens displayed similar failure mode of