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Optimisation of composite patches repairs with the design of experiments method

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ABSTRACT

Composite patches have been recognized as a judicious and effective way of repairing cracks or defects. The determination of the stress intensity factor K at the crack tip is obtained with the use of the finite element method. The run of different simulations allow us to analyse the effect of different parameters that affect this factor such as the size and the intrinsic properties of the adhesive, the patch and the plate. In this paper, we utilise the experimental design method to investigate the effect of these parameters in order to achieve an optimisation of the repair operation. The case taken into consideration is the mode I. We were able to determine which of these parameters are most effective in reaching our goal and which ones should be adjusted to improve the quality of the patch.

1. Introduction

The method of experimental design has been widely used in industry for determining factors that are most important in achieving useful goals in a manufacturing process [1–3]. These factors, under the designer's control, are varied over two or more levels in a systematic manner. Experiments are then performed, according to an orthogonal array to show the effects of each potential primary factor; thus allowing us to perform an analysis that will reveal which of the factors are most effective in reaching our objective and how these factors should be adjusted to optimise it. In the present work we apply the method of experimental design for the optimisation of composite bonded patches.

Composite bonded patches have been widely used to reinforce metallic structures, as they offer several advantages over conventional repairs; they provide better structural integrity; are easier to install, stronger, stiffer, lighter and have a good fatigue performance. They constitute the optimum solution to prevent crack propagation by bypassing the load and producing a reinforcement that retards or stops the crack's propagation. Baker Alan is one of the pioneers of this field [4–6]. Several criteria can be used to characterise a good design patch. The most important is the reduction of the effects of the defect, thus the stress intensity factor .The finite element method allow the abstention of good results; it has been used by many authors among then Megueni et al. [7], Tim et al. [8] and Jones et Chiu [9]. Proper design of the repairs requires that the patch absorbs an appreciable fraction of the load imposed in the vicinity of the crack and that the patch does not debond from the structure under service. This will depend upon many factors among them the intrinsic and geometrical parameters of the patch and the adhesive. The variations of the stress intensity factor as a function of these parameters have been presented in the literature by the above authors. However this has been done by varying one parameter at a time although they interact. The purpose of this work is to improve to this approach by conducting a global study of this phenomenon. We will take, as a first step, into consideration the following parameters: the thickness of the patch, the thickness and the shear modulus of the adhesive. We will use the design of experiment method which proved to be judicious for this kind of investigations. This will allow us to determine the most influents factors that affect the outcome result in this case the value of the stress intensity factor K once we perform this analysis, we will be able to optimise our patch through the determination of its optimum value parameters.

2. Method

In this work, we will consider a rectangular aluminium plate with a central horizontal through-thickness crack. To prevent the propagation of the crack, a non tapered unidirectional graphite/epoxy patch is bonded for repair on one side of the plate with its fibres oriented perpendicular to the crack. The simulations and computing will be done, using the finite element program Franc2D/L developed at Cornell University, Texas [10].

For parameters optimisation of problems with a given objective function, the method of experimental design is a suitable method that can rapidly optimise the varying factors to get a desired outcome. Since our goal is to minimise the stress intensity factor K (SIF), which is a function of several variables whose values can be controlled, it is appropriate to employ the experimental design method. In this particular case we consider three factors that influence the value of K: the respective thicknesses of the patch and the adhesive and the shear modulus of

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the adhesive. The objective being finding the optimum values of these factors that minimise *K*. We will opt for a full experiment design that is all possible combinations of the values of the factors. We will affect to each of them three values which are called levels: patch thickness [0.51–1.30–2.00 mm], adhesive thickness [0.051–0.13–0.25 mm] and G adhesive [480–552–620 MPa]. These values are selected randomly in an ascending order. We therefore, will have 3^3 runs; the orthogonal array in Table 2 represents these experiments.

3. Geometrical model

For our investigation we will consider:

An aluminium plate of 304 length, 152 mm width and 1.30 mm thickness with the following mechanical properties: Young's modulus $E = 72{,}400$ Mpa and Poisson's ratio $\nu = 0.33$.

A central crack of length 38 mm perpendicular to the loading direction exist in the plate. This crack is repaired with a bonded graphite/epoxy unidirectional composite patch with the following mechanical properties (Fig. 1):

$E_1 = 172{,}400$ MPa; $E_2 = E_3 = 10{,}300$ MPa; $G = 4800$ MPa; $\nu_{12} = \nu_{13} = 0.3$; $\nu_{23} = 0.02$.

The patch thickness will take the values er = [0.51–1.30–2.00 mm].

We utilise an FM 73 adhesive with the following variable characteristics:

Shear modulus G = [480–552–620 MPa].

And a variable thickness e_a = [0.051–0.13–0.25 mm].

A tensile stress σ of 140 MPa is applied to the plate perpendicular to the crack direction, thus deal with a pure mode I case (Fig. 1). Fig. 2 shows the typical mesh model used in this study.

4. Results and analysis

Table 1 represents the matrix of the studied phenomena. It contains all the possible combinations obtained with the three parameters, each one of them with three levels.

In Table 2, we have the coefficients of the factors and their interactions. We can see that the most influent factor is the adhesive thickness (2.389) followed closely by the patch thickness (−2364). The coefficient of the shear modulus *G* is far behind (−0.433). Then come in decreasing order the patch thickness/adhesive thickness interaction (−0.167), the patch thickness/modulus *G* interaction (0.130) and finally the *G* modulus/adhesive thickness interaction (0.045). The sign of the coefficients are not taken into account since what matters is the "weight" of the coefficients. These results are comforted by Figs. 1–5; the effect plot is useful for screening design. The effects are sorted from the largest to the smallest. Note that the effects are twice the coefficients as these are the change in the response when the factors vary from the average to the high level. The scaled & centered coefficients plot is used to interpret the results .The scaling makes the

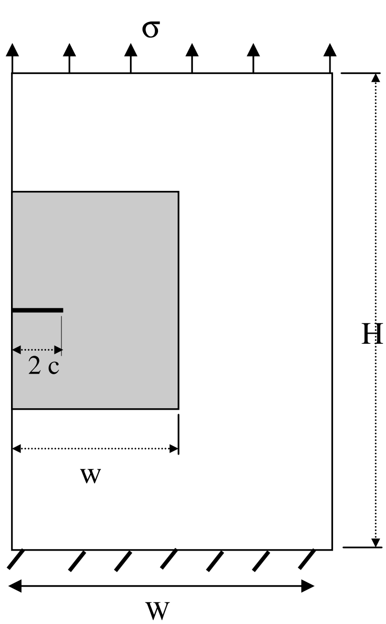

Fig. 1. Geometrical model of the patched structure.

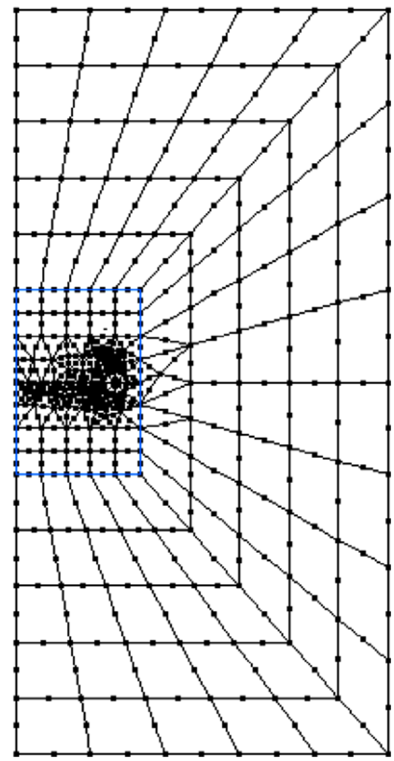

Fig. 2. Typical mesh model.

Table 1
Matrix of the runs

Patch thickness (mm)	*G* adhesive (Mpa)	Adhesive thickness (mm)	SIF (*K*) ($MPa\sqrt{m}$)
0.51	480	0.051	12.6
0.51	480	0.13	15.78
0.51	480	0.25	18.43
0.51	552	0.051	15.22
0.51	552	0.13	15.28
0.51	552	0.25	17.92
0.51	620	0.051	10.9
0.51	620	0.13	14.84
0.51	620	0.25	17.46
1.3	480	0.051	9.94
1.3	480	0.13	12.71
1.3	480	0.25	14.93
1.3	552	0.051	9.55
1.3	552	0.13	12.29
1.3	552	0.25	14.49
1.3	620	0.051	9.21
1.3	620	0.13	11.93
1.3	620	0.25	14.11
2	480	0.051	8.72
2	480	0.13	11.15
2	480	0.25	13.13
2	552	0.051	8.38
2	552	0.13	10.79
2	552	0.25	12.74
2	620	0.051	8.088
2	620	0.13	10.47
2	620	0.25	12.4