RESEARCH ON DYNAMIC STRESS CONCENTRATION FACTOR AROUND THE HOLE UNDER PRIMARY WAVE

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Abstract: Dynamic stress concentration effects caused by stress wave can cause material failure easily. In order to investigate the propagation process of primary wave on the hole-containing plate and the dynamic stress concentration effects around the hole, the spilt Hopkinson pressure bar was used to research the material with holes. Dynamic stress concentration factors of the hole-containing plate were obtained under primary wave with different numbers, sizes, shapes and positions of holes. At the same time, numerical simulation method was used to compare with the experimental results. The results show that the maximum dynamic stress concentration factor of the hole-containing plate is produced in the tangential location of the hole and the wave propagation direction. The shape of the hole plays a key role to the location where the dynamic stress concentrated. The dynamic stress concentration effect around the hole is obviously weakened by arranging the smaller hole ahead, meanwhile, the influence of different sizes and positions of the smaller hole is considered. Therefore, the research on dynamic stress concentration factor around the hole under primary wave has practical value to the design of hole-containing plate.
Keywords: primary wave, wave propagation, dynamic stress concentration factors, hole-containing plate

1. Introduction

Elastic plate structures are widely used in aviation, aerospace, shipbuilding and civil engineering, and engineering design often requires holes in the flat structure[1]. The propagation of stress waves in an infinite homogeneous medium is usually carried out by a fixed velocity along a fixed path. However, if the medium contains holes, the wave propagation path will change accordingly, and produce scattering and diffraction, resulting in that the stress around the hole is different from the stress generated by undisturbed fluctuations in the same point, that is dynamic stress concentration. The elastic wave scattering and dynamic stress concentration on the hole-containing plate are directly related to the service life of the plate structure.

For the case of stress concentration under static conditions, a more mature solution method has been proposed. The complex function method proposed by N.I.Muskhelishvili et al.[2] has successfully solved the static stress concentration problem of the flat with openings described by the bi-harmonic equation. In addition, Nishida Masako's handbook and Sarven's monograph show the results of various stress concentration factors. However, for the problem of dynamic stress concentration, it is more complex because of the stress wave theory, and the achievements obtained before the 60s of last century are less. In 1962, Bao Yixing published an article on the study of the steady-state wave incident in the infinite elastic thin plate with circular holes dynamic stress concentration problem by the eigenfunction expansion method. Since then, the theoretical analysis methods of dynamic stress concentration include wave function expansion method, integral equation method, multi-polar coordinate method, integral variation method and perturbation method[3-7]. Hu Chao et al. [8]studied the elastic wave scattering problem on a flat plate with a hole by using the method of complex function. The multi-pole coordinate method and the complex variable function method are used to analyze the dynamic problems of the shallow holes in the half-space by WANG Guo-qing and LIU Dian-kui. He Zhongyi et al. studied on the scattering of SH waves by the method of wave front expansion. Ma Xingrui et al. studied on the diffraction of elastic wave and dynamic stress concentration of orthotropic plate openings by perturbation method. Theoretical analysis of dynamic stress concentration requires complex mathematical tools, which are difficult to be grasped by engineers, and the analysis of the above literature is considered in an infinite region rather than a limited area, and engineering problems usually occur in a limited area. Therefore, it is very important to study the dynamic stress concentration problem of plate with holes under the action of elastic wave in limited area.

In this paper, the experimental research and simulation research of the hole-containing plate are carried out by means of split Hopkinson pressure bar and finite element analysis software. Meanwhile, we investigate the propagation process of primary wave on the hole-containing plate and the dynamic stress concentration factors of the hole-containing plate with different shapes, sizes, quantity and positions.

2. Experimental research

2.1 Experimental material and specimen

We used 45 # carbon steel material to make experimental specimen, its basic performance parameters are shown in Table 1. The size of the experimental specimen is 200mm long, 200mm wide and 16mm thick. Four flats of 16mm×16mm are obtained by processing the four corners of the plate. The experimental specimen is shown in Fig. 1 (Unit: mm).

Table 1: the basic performance parameters of 45# carbon steel

Density (g/cm^3)	Modulus of elasticity (GPa)	Poisson's ratio	Yield strength (MPa)	Tensile strength (MPa)
7.85	210	0.269	355	600

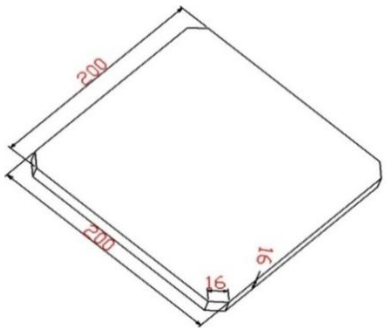


Figure 1: Schematic diagram of experimental specimen

2.2 Experimental device and principle

The schematic diagram of the split Hopkinson pressure bar is shown in Fig.2. The principle of the experiment setup is to measure the incident wave, reflected wave on incident bar and the transmitted wave on transmission bar by using the strain gage, and then, the stress-strain relationship of the specimen can be obtained according to the one-dimensional stress wave theory. At the same time, the stress wave propagation on the specimen can also be obtained directly by sticking the strain gage on the specimen. We used the split Hopkinson pressure bar with diameter of 16mm experimental device to do experiments, as shown in figure 3. The P wave can be generated in incident bar by the impact of striker. In this paper, the most important part is the propagation process of P-wave on the specimen and the dynamic stress concentration coefficient on the boundary of the hole in the specimen under P-wave.

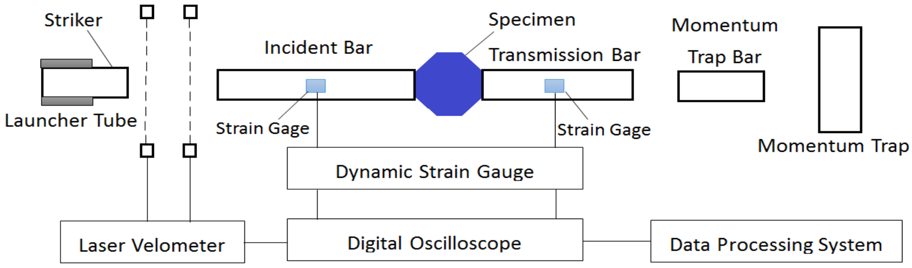
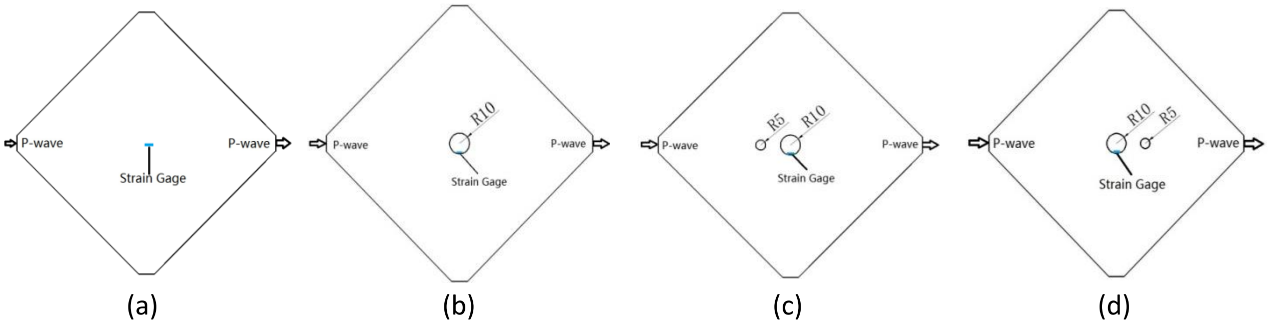


Figure 2: Schematic diagram of the split Hopkinson pressure bar

Figure 3: Diagram of experimental device

2.3 Experimental process

By designing different holes on the experimental specimen, we can get various experimental specimens with different numbers, sizes, shapes and positions of holes, as shown in Figure 4. Their dynamic stress concentration factors of the hole-containing plates under primary wave were studied. From the figure 4, we could know the direction of propagation of P-wave and the sticking position of strain gauges, and we carried out 6 experiments for each specimen. First of all, the specimen without holes was tested. Before the experiment, the resistance strain gage was pasted at the centre point of the specimen. During the experiment, the impingement surface of the incident bar, the surface hit by the incident bar, the specimen surface through the wave, the hit surface of transmission bar by the same straight line and contact closely. Finally, the dynamic strain gauge was used to collect and measure the voltage change of the strain gauge. Therefore, the propagation process of the P-wave on the specimen plate and the stress at the centre of the plate specimen were observed. Similarly, experiments were performed on specimens with various holes. Each specimen pasted a strain gage attached to the inside of the hole along the propagation direction of the P-wave to measure the stress along the propagation direction of the P-wave. The positions of the strain gages were determined by simulation. Compared with the stress value at the centre of the specimen without holes, the dynamic stress concentration factors around the hole under P-wave were obtained.



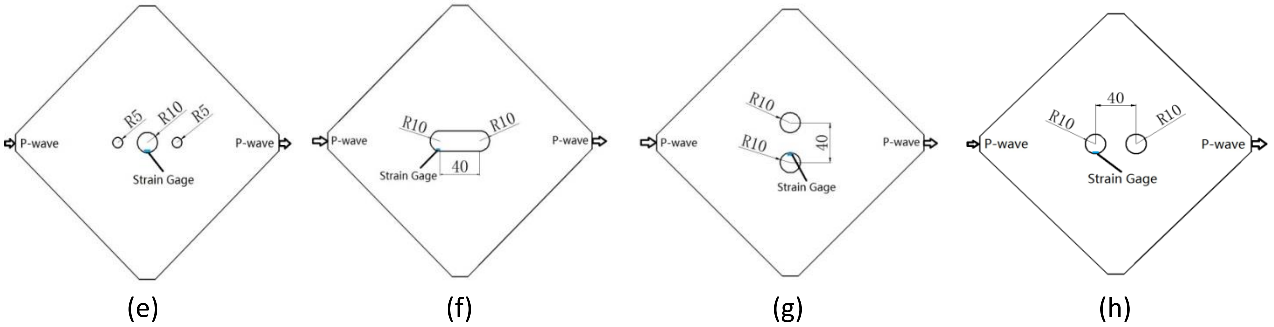
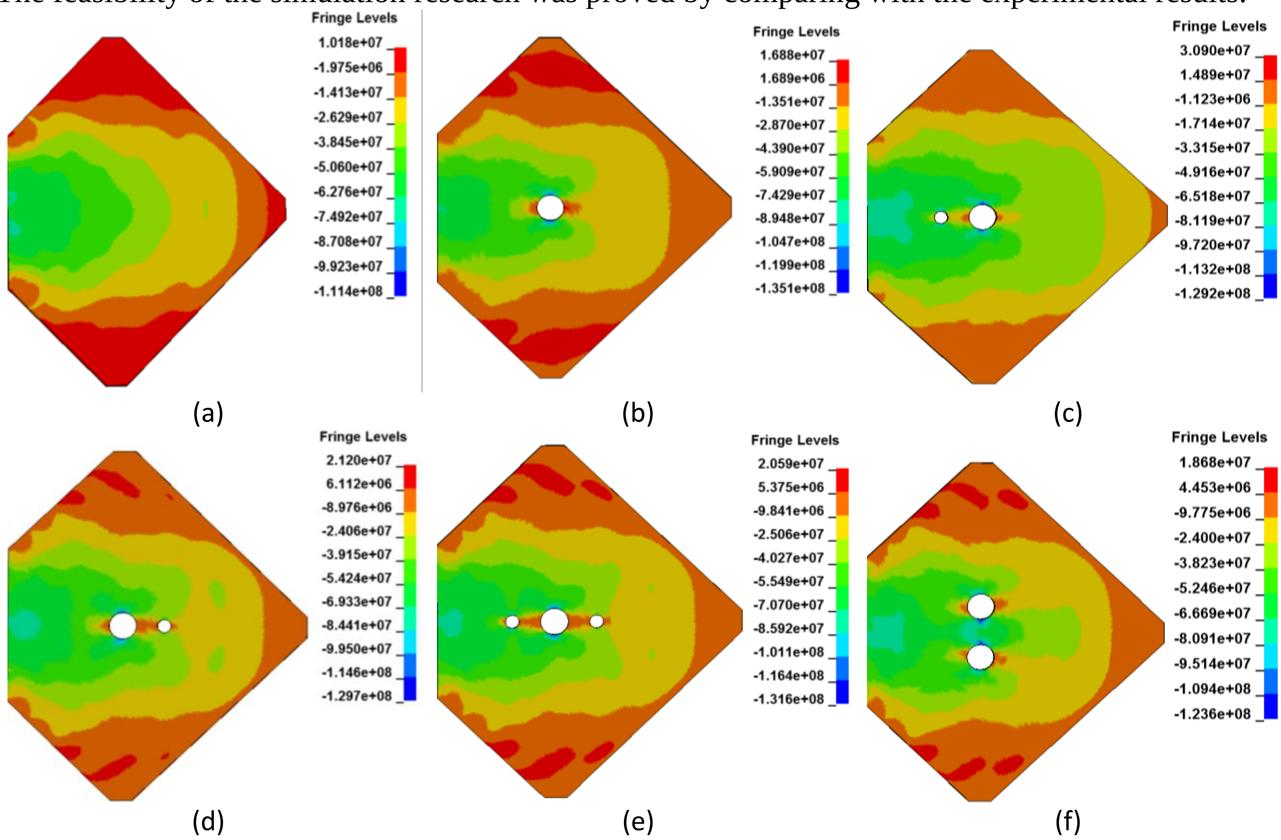


Figure 4: Plan of experimental specimen for (a): specimen without holes (b): specimen a (c): specimen b (d): specimen c (e): specimen d (f): specimen e (g): specimen f (h): specimen g

3. Simulation research

The finite element analysis software LS-DYNA was used to simulate the same plate specimens. First of all, the elastomer was selected as the analytical model material, and the definition of the analytical model material parameters was consistent with the parameters in Table 1. Secondly, the 3D analysis model was established, its size is the same as experimental specimen. Thirdly, meshing the analysis model, in order to get the more accurate simulation results, the density of the grids around holes is bigger than other parts. In addition, the initial velocity was applied to the striker, the contact condition and the solved time were set, the K file was generated, and the K file was submitted for solving. Finally, the finite element analysis results were analyzed, and the stress cloud pattern of the specimen could be obtained as shown in Figure 5. The positions of the strain gages were determined. The feasibility of the simulation research was proved by comparing with the experimental results.



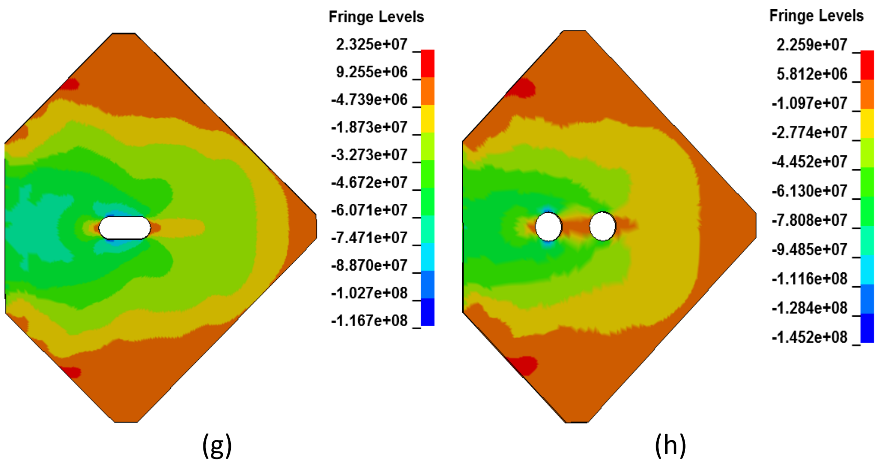


Figure 5: Stress cloud of simulation research for (a): specimen without holes (b): specimen a (c): specimen b (d): specimen c (e): specimen d (f): specimen e (g): specimen f (h): specimen g

4. Results and discussion

The dynamic stress concentration factors around the hole of the specimen under P-wave were obtained through the comparison research between the experiment and the simulation. At the same time, we investigated the important factors that influence the dynamic stress concentration coefficient around the hole of the specimen by changing the size, location and quantity of the holes on the specimens. When analyzing the experimental and the finite element results, we put the maximum stress value on incident bar as the datum stress, and nondimensionalize the stress of the strain gage on the specimens. We defined the dynamic stress concentration factor around the hole under primary wave as K_i, K_i meets the following formula:

$$K_i = \frac{\dim(\sigma_{i\max})}{\dim(\sigma_{0\max})} \tag{1}$$

Formula (1): dim stands for the dimensionless, $\sigma_{i\max}$ is the stress peak around the hole under P-wave in the hole-containing specimen, $\sigma_{0\max}$ is the stress peak at the centre of the specimen without holes under P-wave.

The experimental and simulation data were processed by Eq. (1), and the dynamic stress concentration factors were obtained under the experimental and simulation methods, as shown in Table 2. From Table 2, it can be seen that the dynamic stress concentration factors are in the range of 2.43 to 3.45 under experimental conditions. Under the simulation conditions, the dynamic stress concentration factors are in the range of 2.58 to 3.11, and the dynamic stress concentration factor is more concentrated than the experimental one, therefore, the simulation method is feasible to this problem because the error is less than 10%.

Table 2: Experimental and simulation results and errors

Specimen	K_i (Experiment Result)	K_i (Simulation Result)	Error
Specimen a	3.12	3.03	2.88%
Specimen b	2.43	2.58	6.17%
Specimen c	3.02	3.02	0
Specimen d	2.38	2.58	8.40%
Specimen e	2.82	2.89	2.48%
Specimen f	3.45	3.11	9.86%
Specimen g	3.45	3.18	7.82%

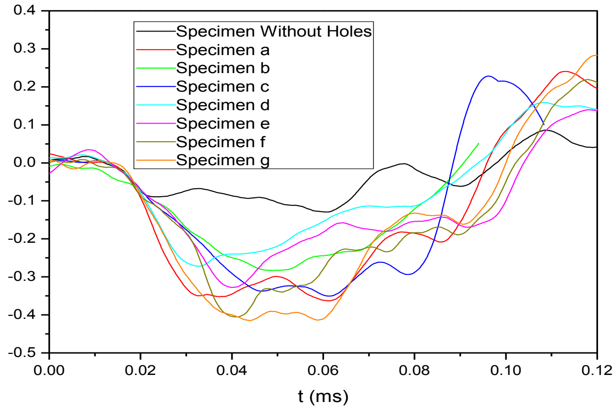


Figure 6: Stress waveforms of experimental research (Dimensionless)

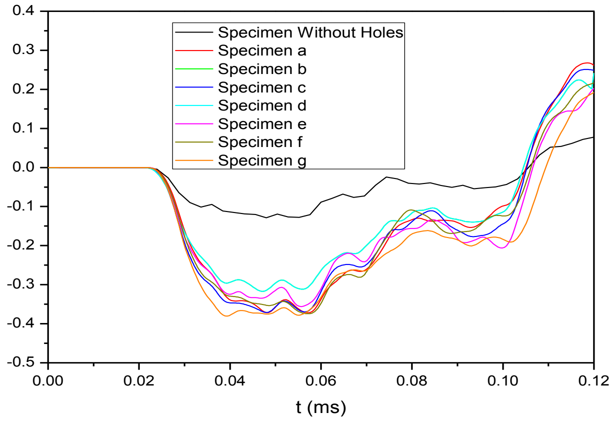
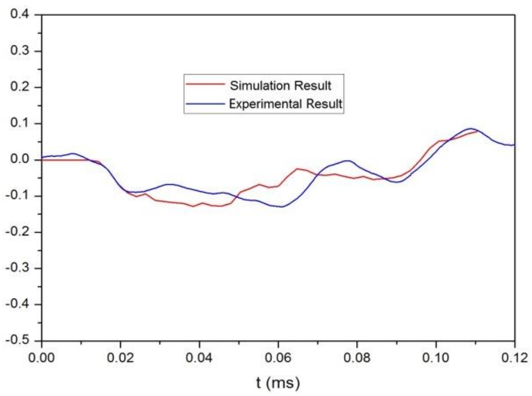
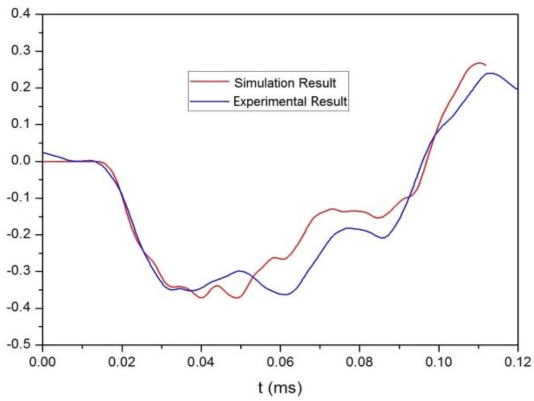


Figure 7: Stress waveforms of simulation research (Dimensionless)



(a)



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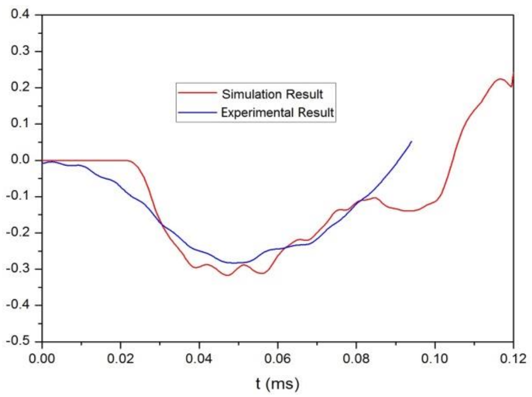

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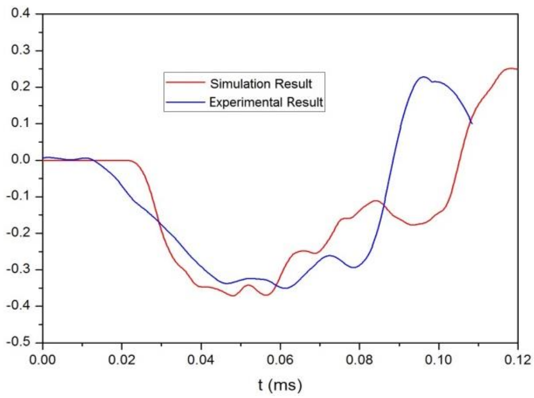

(d)

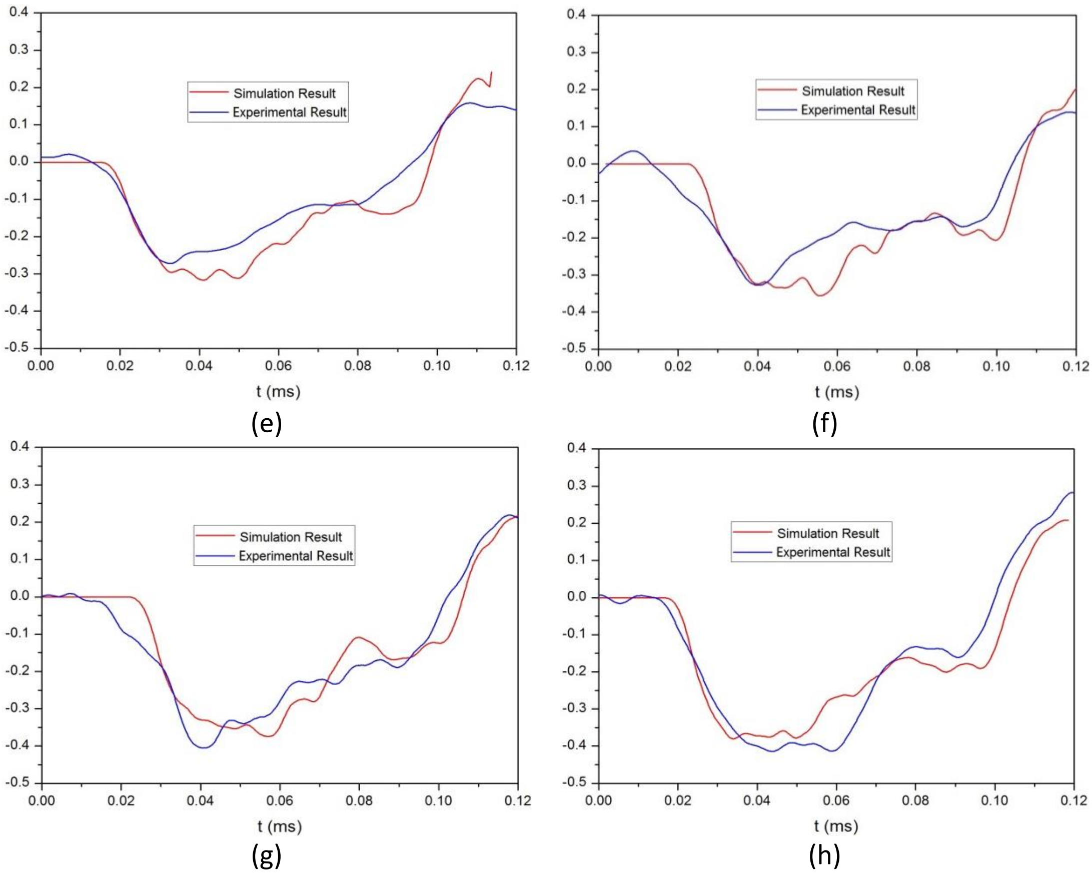

Figure 8: Stress waveforms comparison of simulation and experimental results (Dimensionless) for (a): specimen without holes (b): specimen a (c): specimen b (d): specimen c (e): specimen d (f): specimen e (g): specimen f (h): specimen g

Under the experimental and simulation conditions, the dimensionless stress waveforms of the specimens Fig. 6 and Fig. 7 can be plotted by collecting stress at the centre of the specimen without holes plate and around the hole in the specimen with holes. It can be seen from Fig. 6 that the dynamic stress concentration effect around the centre hole is obviously weakened by arranging the smaller hole ahead. On the contrary, the smaller hole arranged behind has little effect on the dynamic stress concentration around the centre hole of the specimen. When the hole is arranged on the plate specimen just like the specimen f, the dynamic stress concentration effect around the hole is obviously larger than that around the centre single hole. It can be seen from Fig. 7 that a similar rule is obtained with experiments under the simulated condition, and the convergence of waveform is better than the experimental one. Finally, we drew the dimensionless stress comparison waveforms to each specimen under both experimental and simulation conditions, as shown in Fig. 8. The Fig. 8 shows good coincidence between these two methods, which proves the feasibility of the simulation method.

5. Conclusions

In this paper, the dynamic stress concentration factors and the propagation of P-wave on the specimen under P-wave were studied by using split Hopkinson pressure bar and LS-DYNA finite element software under the experimental and simulation conditions respectively. At the same time, we investigated the changing law of the dynamic stress concentration factors by changing the size, the layout, the number and the shape of the holes on specimen.

The main conclusions are as follows:

(1) The dynamic stress concentration factor around the hole in the hole-containing specimen is about 3, and it is related to the diameter, layout, number and shape of the hole. The dynamic stress

concentration effect around the centre hole is obviously weakened by arranging the smaller hole ahead.

(2) The shape of the hole is the decisive factor for the location of the dynamic stress concentration. The maximum dynamic stress concentration factor of the hole-containing plate is produced in the tangential location of the hole and the wave propagation direction.

(3) The experimental and simulation results are in good coincidence with each other, which proves the feasibility of the simulation method.

Therefore, the study of the dynamic stress concentration of the plate with holes under the P-wave in the limited area is of great significance to the design of the hole on the hole-containing plate.

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REFERENCES

1 Fang X Q, Jin H X, Wang B L. Dynamic interaction of two circular lined tunnels with imperfect interfaces under cylindrical P-waves. International Journal of Rock Mechanics and Mining Sciences, 79: 172-182, (2015).

2 Muskhelishvili N I. Some basic problems of the mathematical theory of elasticity. Springer Science & Business Media, (2013).

3 Wang J H, Zhou X L, Lu J F. Dynamic stress concentration around elliptic cavities in saturated poroelastic soil under harmonic plane waves. International Journal of solids and Structures, 42(14): 4295-4310, (2005).

4 Yi C P, Lu W, Zhang P, et al. Effect of imperfect interface on the dynamic response of a circular lined tunnel impacted by plane P-waves. Tunnelling and Underground Space Technology, 51: 68-74, (2016).

5 Fang X Q, Liu J X, Zhang L L, et al. Interface stress around a nanosized spherical inhomogeneity under asymmetric dynamic loads. Science China Physics, Mechanics and Astronomy, 55(10): 1844-1854, (2012).

6 Yang Q Q, Gao C F, Chen W T. Stress concentration in a finite functionally graded material plate. Science China Physics, Mechanics and Astronomy, 55(7): 1263-1271, (2012).

7 Luo L, Xiang Y, Wang Q. Stress concentration factor expression for tension strip with eccentric elliptical hole. Applied Mathematics and Mechanics, 33: 117-128, (2012).

8 Zhou C, Hu C, Ma F, et al. Elastic wave scattering and dynamic stress concentrations in exponential graded materials with two elliptic holes. Wave Motion, 51(3): 466-475, (2014).