A Study on Counterintuitive Behavior of Clamped Square Plates under Blast Loading

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Abstract. In order to study the counterintuitive behaviour of the clamped square plates under blast loading, numerical simulation and experimental research were carried out on the clamped square aluminium plate. The finite element software is used to simulate the dynamic response of plate under the blast loading. It is found that the counterintuitive behaviour occurred only under the condition when the overpressure is low and the positive pressure time is short. And this deformation mode occurred between elastic deformation and large plastic deformation. The explosion tests were carried out to obtain the counterintuitive behaviour of plates, and the range of the explosion load which caused the counterintuitive behaviour was clarified.

1. Introduction
Counterintuitive behavior is an appearance of final deflections of plate which is contrary to the direction of the blast loading [1]. Counterintuitive behavior occurs because the dynamic response of the plate obeys nonlinear equations of motion and is extremely sensitive to changes of the load parameters in a specific range [2]. This special dynamic behavior is related to coupling effects of internal force and large plastic deformation after removal loading [3]. Guiying Wu [4-6] studied the effects of load parameters, plate material and plate size on counterintuitive behavior by finite element method, and confirmed the objective existence of counterintuitive behavior in the simply supported circular plate by the explosion experiment. At present, there are few studies focused on counterintuitive behavior. And in the existing studies, most of them adopts numerical simulation, while experimental investigation was ignored [7].

In this paper, the finite element software LS-DYNA will be used to study the influences of peak overpressure and positive pressure time on the deformation within the ranges where counterintuitive behavior occurs. We also tend to obtain the counterintuitive behavior of plates under the load of different charge masses and explosion distance by explosion experiment.

2. Numerical Simulation
The finite element software LS-DYNA is used to study the influences of peak overpressure and positive pressure time on the deformation within the ranges where counterintuitive behavior occurs.
2.1. Finite element model

The clamped square plate has the dimension of 25cm×25cm×0.1cm and was modeled as SHELL163 element, with 125×125 elements along edges. The material of the plate is 1060 aluminum and this material was defined as *MAT_JOHNSON_COOK with *EOS_GRUNEISEN. The density of 1060 aluminum is 2.7g/cm³, the elastic modulus is 70GPa, the Poisson's ratio is 0.33, and the remaining parameters are shown in Table 1 and Table 2.

**Table 1.** Johnson-Cook constants of 1060 aluminum.

| A/MPa | B/MPa | n   | C   | m | T_room/k | T_melt/k | D1   | D2   | D3   | D4   | D5   |
|-------|-------|-----|-----|---|----------|----------|------|------|------|------|------|
| 108   | 100   | 0.183 | 0.001 | 1 | 300      | 933      | 1    | 0.13 | -1.5 | 0.011 | 0    |

**Table 2.** Gruneisen EOS constants of 1060 aluminum.

| C     | S1   | S2   | S3   | γ0 | a   | E0   | V0   |
|-------|------|------|------|----|-----|------|------|
| 0.5386| 1.399| 0    | 0    | 1.99| 0.46| 0    | 1    |

In order to facilitate the change of the explosion load parameters, an explosion load is applied to the plate by defining a load curve. The equation for the load curve is shown as follows [8]

\[
p(t) = p_m \left(1 - \frac{t}{t_d}\right)e^{-t/t_d}
\]  

(1)

Where \( p_m \) is the peak overpressure and \( t_d \) is the positive pressure time. This function can well describe the actual overpressure curve of shock wave. The shape of load curve is shown in Fig. 1. Both \( p_m \) and \( t_d \) can be calculated according to empirical formulas (2) and (3) [9].

\[
p_m = \begin{cases} 
0.084 + 0.27 \frac{Z}{Z^2} + 0.7 \frac{1}{Z^3}, & Z \leq 1 \\
0.076 + 0.255 \frac{Z}{Z^2} + 0.65 \frac{1}{Z^3}, & 1 < Z \leq 15
\end{cases}
\]  

(2)
\[ t_d = 10^{-3} \times \sqrt[3]{W \sqrt{R}} \]  \hspace{1cm} (3)

Where \( W \) is the mass of the explosive TNT, \( R \) is the explosion distance, and \( Z = \frac{R}{W^{1/3}} \) is the scaled distance.

2.2. Influence of peak overpressure on counterintuitive behaviour
In order to study the influence of peak overpressure on counterintuitive behavior, the positive pressure time is taken as 1ms (In the small equivalent explosion test, the positive pressure time is usually around 1ms), and the peak overpressure \( p_m \) is changed within the range of 0.1MPa-0.5MPa. By observing the deformation of plate under different peak overpressure, the results show that when \( p_m \) is between 0.15 and 0.25 MPa, the counterintuitive behavior of plate occurs; when \( p_m \) is less than 0.15 MPa, the plate vibrates near the initial position; When \( p_m \) is greater than 0.25 MPa, the large plastic deformation occurs. This indicates that the mode of counterintuitive behavior is between the elastic deformation and the large plastic deformation. The center deflection-time history curve is shown in Figure 2, and the typical counterintuitive behavior process of plate is shown in Figure 3. From these two pictures, we can conclude that the plate first moves to the direction of loading under the blast load. When the deformation reaches its maximum in the forward direction, the center of the plate begins to move in the opposite direction until the plate vibrates in the opposite direction.

2.3. Influence of positive pressure time on counterintuitive behaviour
In order to analyze the influence of the shock wave positive pressure time on the counterintuitive behavior, the peak overpressure of the load curve is set as 0.20 MPa, and then change the positive pressure time \( t_d \). It is found that when \( t_d \) is greater than 1.4ms, the deformation mode of plate is large plastic deformation; when \( t_d \) is less than 1.4ms, the counterintuitive behavior occurs, as shown in Figure 4. This indicates that under the blast load of the same peak overpressure, the shorter the positive pressure action time is, the more favorable the counterintuitive behavior occurs.
3. Experimental study on deformation of clamped square plates

In order to further study the counterintuitive behavior of the clamped square plates under blast loading, we carry out the explosion test of different TNT masses to study the deformation of the plate under blast loading.

3.1. Experimental procedure

The clamped square plate has the dimension of 35cm×35cm×0.1cm. Sixteen holes with a diameter of 8.5mm are opened around the square plate for fixing with the flange. The actual load surface is a square area of 25cm×25cm (See Figure 5). In order to ensure the normal incidence of explosion shock wave, the plate is installed in a standing position: the plate is clamped by flange and installed on the support structure, and the plate is perpendicular to the ground, as shown in Fig. 5. The plate is far from the ground, avoiding the influence of Mach wave.

Three kinds of TNT mass explosion experiments (432.5g, 632.5g and 832.5g) were designed to study the deformation of plate. For the same TNT mass explosion test, four plates were placed at different distances. The explosion center is 1.2m from the ground and is level with the center of the plate. Considering that the range of peak overpressure which cause counterintuitive behavior of the plate is 0.15 MPa to 0.25 MPa predicted in the numerical simulation, the explosion distance is set to 0.8 m to 2.4 m. At these explosion distances, it can be approximately assumed that the explosion shock wave uniformly act on the surface of the plate, and the plate is less likely to be affected by the detonation products.

3.2. Experimental observations

After the explosive is detonated, the support structure and the flange for clamping the plate are approximately unreformed, and the deformation of some of the plates is shown in Figure 6. In Fig. 6,
all of the three plates a, b and c occurred counterintuitive behavior. In particular, there is a distinct circular groove in the center of the plate in Fig. 6a, which is consistent with the “cap-like” in the counterintuitive behavior mentioned in Ref. [4]. In Fig. 6, the deformations of b and c are substantially symmetrical, and the position where the deformation deflection is the largest is at the center of the plate. The deformation modes of the d, e, and f plates in Fig. 6 are large plastic deformation, partial tearing in the central area, and shear failure at the boundary respectively. The deformation degree of the plate is quantified by the final deflection $\omega$ of the center point of the plate. The final deflection $\omega$ was measured with a depth meter, and $\omega$ where plastic deformation occurred was recorded as positive, and $\omega$ where counterintuitive behavior occurred was recorded as negative, and the results were shown in Table 3.

![Figure 6. Picture of test plate](image)

| $Z/m\cdot kg^{-1/3}$ | $W/g$ | $R/cm$ | Deformation mode | $\omega/cm$ |
|----------------------|-------|--------|------------------|------------|
| 2.80                 | 632.5 | 240.0  | C                | -0.90      |
| 2.55                 | 432.5 | 193.0  | C                | -0.74      |
| 2.50                 | 632.5 | 214.5  | C                | -1.43      |
| 2.31                 | 432.5 | 175.0  | C                | -1.03      |
| 2.25                 | 632.5 | 193.0  | C                | -1.00      |
| 1.95                 | 432.5 | 147.2  | C                | -0.01      |
| 1.77                 | 432.5 | 134.0  | L                | 2.76       |
| 1.56                 | 832.5 | 147.2  | L                | 3.89       |
| 1.56                 | 632.5 | 134.0  | L                | 3.51       |
| 1.42                 | 832.5 | 134.0  | L                | 4.88       |
| 1.17                 | 832.5 | 110.0  | T                | /          |
| 0.85                 | 832.5 | 80.0   | S                | /          |

*C indicates counterintuitive behaviour, L indicates large plastic deformation, T indicates partial tearing in the central area, S indicates shear failure at the boundary*
For the convenience of analysis, the data in Table 1 was plotted with the scaled distance Z as the horizontal axis and the deflection $\omega$ as the vertical axis (See Figure 7.).

![Figure 7. Deformation mode of plate](image)

Combined with Table 3 and Figure 7, it is concluded that for the plate used in this paper, as the scaled distance increases, the deformation modes of the plate are shear failure at the boundary, partial tearing in the central area, large plastic deformation, and counterintuitive behavior, respectively. The counterintuitive behavior occurs when the scaled distance Z is between 1.95 and 2.80 m·kg$^{-1/3}$, that is, the peak overpressure is between 0.09 MPa and 0.19 MPa. This is basically consistent with the estimated peak overpressure range by numerical simulation. Since the counterintuitive behavior of the plate is subject to a low peak overpressure and a short positive pressure time, the energy applied to the plate by the shock wave is also small. This results in a low degree of deformation of the plate where counterintuitive behavior occurs, and all these plates had a center final deflection of less than 1.5 cm.

4. Conclusion
The counterintuitive behavior process of clamped square plate under the blast loading was studied by numerical simulation, and the overpressure range which could cause counterintuitive behavior of the plate was estimated. It is found that the counterintuitive deformation occurs only under the condition of the peak overpressure is low and the positive pressure time is short, and this deformation mode occurs between elastic deformation and large plastic deformation. Through the explosion experiment, a series of counterintuitive behavior data of plate under blast loading was obtained. For the clamped square plate used in this paper, the counterintuitive deformation occurs only when the peak overpressure is between 0.09 MPa and 0.19 MPa.

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