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Parametric Study on Optimum Angle of V-Shaped Plate to Mitigate Blast Load Utilizing LS-DYNA

(Kajian Parametrik pada Sudut Optimum Kepingan Bentuk V untuk Mengurangkan Beban Letupan Menggunakan LS-DYNA)

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ABSTRACT

This paper presents the parametric studies to obtain the optimum V-shaped angle plate due to blast load by using numerical simulations i.e., LS-DYNA. Constant magnitudes of mass of TNT and standoff distance were used while the angle of the V-shaped plate was varied in 5 °' interval from 60 ° down to 10 °. This study found that the optimum V-shaped angle plate that could mitigate the maximum amount of blast load while experiencing minimal deformation at the vertex of the V-shaped plate was 25 °. Detailed parametric steps were presented in this study in order to arrive at the optimum angle of V-shaped plate to mitigate the blast load.

Keywords: V-shaped plate; LS-DYNA; blast loading; numerical simulation; optimum angle

ABSTRAK

Kertas penyelidikan ini mengemukakan kajian parametrik untuk mendapatkan plat sudut berbentuk V yang optimum kerana beban letupan dengan menggunakan simulasi berangka iaitu LS-DYNA. Kebesaran jisim tetap TNT dan jarak berhenti digunakan sementara sudut plat berbentuk V bervariasi dalam selang 5 darjah dari 60 darjah hingga 10 darjah. Kajian ini mendapati bahawa plat sudut berbentuk V optimum yang dapat mengurangkan jumlah maksimum beban letupan ketika mengalami ubah bentuk minimum pada bucu plat berbentuk V adalah 25 darjah. Langkah-langkah parametrik terperinci dinyatakan dalam kajian ini untuk mencapai sudut optimum plat berbentuk V untuk mengurangkan beban letupan.

Kata kunci: Plat berbentuk V; LS-DYNA; pemuatan letupan; simulasi berangka; sudut optimum

INTRODUCTION

An explosion that occurred in Chelsea, New York, USA on 17 September 2016 that injured 29 people was the latest brutal attack on innocent human beings which could also happen anywhere in the world (CNN 2016; CNN 2019a, 2019b; MSN 2019). New York police suspected an improvised pressure cooker was used to produce the explosion and a witness said that his whole apartment building trembled due to the effect of the explosion. Explosive devices are favoured among terrorists for the past decades mainly due to its destructing and devastating effects besides being able to produce large casualties in a very short time. When an explosive device explodes, an intense pressure is produced and expands away from the source in milliseconds (Smith & Hetherington 1994).

Extensive studies on responses of structures due to blast loadings have been widely published in the open literature to find ways on how to further protect human beings and increase the protective capabilities of structures from explosion related events (Al-Thairy 2016; Avachat & Zhou 2016; Chen et al. 2016; Micallef et al. 2016; Pickerd et al. 2016; Spiller et al. 2016; Yao et al. 2016; Zhang et al. 2016; Zheng et al. 2016; Zhu & Khanna 2016; Suhaimi et al. 2017; Md. Isa et al. 2017; Huang et al. 2019; Li et al. 2019; Ren et al. 2019; Rigby et al. 2019; Ruggiero et al. 2019).

Neuberger and his co-researchers (Neuberger et al. 2009) performed studies on the importance of springback effects of armor plate due to blast loading. It was observed that during blast loading of the armor plate, the transient deflection was greater than the residual (final) deflection and this significant factor must be included when designing armor plates. Three numerical simulations were produced to predict the three experimental blast tests of rolled homogeneous armor plates and good agreements were achieved. Wensu and his co-researcher (Chen & Hao 2012) performed numerical simulation of solid compound blast door panel due to blast loading and used an experimental test to validate the simulation result which accomplished a good agreement. Then, they performed several parametric investigations utilising the numerical simulations method and showed that for the same weight, the multi-arched-surface structure door panel had managed to absorb greater blast load as compared to the current solid compound blast door panel. Welded steel containers that were fully enclosed and flanged were studied to examine the structural response and failure mechanism due to internal blast loading (Pickerd et al. 2016). Initially, they used shell elements in their numerical analysis to predict the experimental internal blast test and the numerical simulation results gave good predictions of deformations and strains at the central area of the containers but gave poor predictions at the welded joints of the container. They replaced the shell elements with Langragian improved elements to predict the strains in the welded joints but it still under-predicted the experimental test data. These were due to the limited capabilities of the numerical simulation to model the imperfection of the welding i.e., porosity.

V-shaped plates that included angles of 46 ° and 90 ° (Warfare 2018a) are currently used as a blast mitigation structure in the undercarriage area of armor personal vehicle against minefield explosions (see Figure 1). Chung and his co-researchers (Chung et al. 2012) performed small scale experimental tests and also conducted numerical simulations of V-shaped plates due to blast loading, where the varied angles of the V-shaped plates were 180 °, 150 °, 120 °, 90 °, and 60 °. They found that V-shaped angle plate of 60 ° had the least physical deflection which showed it managed to mitigate most of the blast loading effects at its mid-point vertex of the V-shaped plate. In this present paper, the authors intend to further investigate and conceivably find the optimum angle of the V-shaped plate against blast loading (V-shaped plates angles that are lower than 60 °) since the previous work by Chung et al. (2012). (Chung et al. 2012) ceased at 60 ° and did not go any lower than 60 ° of the V-shaped plate's angle because the projected areas from a single unit of V-shaped plate of 60 ° could cover a large area of the undercarriage of the armored personal vehicle. This paper intends to study the response of V-shaped plates of lower than 60 ° angles so that new geometric shapes, e.g., using multiple V-shaped plates in the design instead of a single V-shaped plate, can be used to further reduce and mitigate the blast loading effects.

FIGURE 1. An armored personal vehicle manufactured by BAE Systems that utilizes the V-shaped plate geometry

Source: Military-Today (2006; Warfare 2018b)

METHODOLOGY

NUMERICAL SIMULATION

LS-DYNA, a multi-purpose explicit and implicit finite element program, was used to analyse the nonlinear response of structures which was developed by Livermore Software Technology Corporation, USA (LSTC 2011).

This software was utilised to perform the numerical simulations to find the optimum angle of V-shaped plates due to blast loadings LS-DYNA software which is well known for its strengths in solving explicit time integration calculations; for example, vehicle crash phenomena, bullet penetration, and explosion related scenarios. In this study, the *LOAD BLAST ENCHANCED command, a simple modeling approach that did not take into the consideration of the surrounding air, was used to simulate the explosion events, whereby the blast pressure will be applied directly to the V-shaped plates and able to produce reasonable results.

MODELING THE GEOMETRY OF THE V-SHAPED PLATE

Figure 2 shows the three-dimensional model of the V-shaped plate constructed by using a preprocessor software i.e., LS-PREPOST (LSTC 2011). Point ‘A’ was the starting position of the V-shaped plate model with (0, 0, 0) coordinate, while point ‘C’ was the end position of the V-shaped plate model. The length between point ‘A’ and point ‘C’ was 0.3 m, thus point ‘C’ was located at (0.3 m, 0, 0) coordinate. The center point of the TNT explosive was constantly fixed to point ‘B’ (with ‘X’ marked) for all of the numerical simulations in this paper. Point ‘B’ was the mid-section of the vertex of the V-shaped plate with a location of (0.15 m, 0, 0.03 m) coordinate. The length of edges ‘D’ and ‘E’ was 0.3 m and the perpendicular distance between edges ‘D’ and ‘E’ was 0.3 m, which would produce a projected area of 0.3 m x 0.3 m in the ‘x-y’ plane while point ‘F’ represented the angle of the V-shaped plate. Validation studies on V-shaped model together with the mesh convergence study on the model have been successfully performed and it was found that an element size of 0.005 m x 0.005 m with four node quadrilateral shell elements that generated a total of 13 920 elements gave optimum result with reasonable CPU time (Othman et al. 2016).

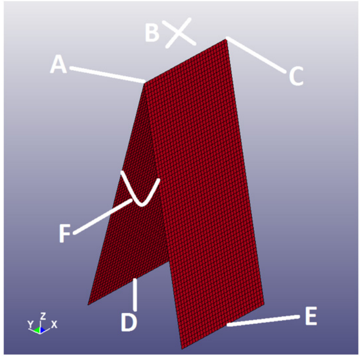


FIGURE 2. A three dimensional V-shaped (or could also be viewed as an inverted V-shaped) plate finite element analysis model

EXPLOSIVE PARAMETERS

A 0.2 kg of TNT explosive was applied to point ‘B’ (see Figure 2) with a stand-off distance of 0.03 m; located above the vertex of the V-shaped plate. In LS-DYNA, the *LOAD_BLAST_ENHANCED command was utilized to model and represent the 0.2 kg of TNT explosive in the simulation. This *LOAD_BLAST_ENHANCED command produced spherical free-air burst with no amplification of the initial shock wave due to the interaction with the V-shaped plate when it was utilized in the simulation analysis. Both of the top surfaces of the V-shaped plate that were directly exposed to the blast loading pressure of the TNT explosive were grouped under *LOAD_BLAST_SEGMENT_SET command. Both of these sets of commands i.e., the source of explosion and the structure that received the blast loading pressure were needed in performing the blast loading simulation analysis events in LS-DYNA.

MATERIAL PROPERTIES AND BOUNDARY CONDITIONS OF THE V-SHAPED PLATE

Table 1 and Table 2 show the mechanical properties and the Johnson-Cook dynamic material properties, respectively, for the V-shaped plate made from DOMEX 700 steel (Chung et al. 2012). To accommodate the high strain rate phenomenon that occurred on the V-shaped plate due to the blast loading phenomenon, *MAT_SIMPLIFIED_JOHNSON_COOK command was utilized in the analysis. The V-shaped plate had a uniform thickness of 0.002 m throughout its plate and was modelled as *SECTION_SHELL that utilized Belytschko-Tsay shell element formulation. In an experimental test performed by Chung and his co-researchers (Chung et al. 2012), a diagram similar to their experimental setup as shown in Figure 2 with both of the edges i.e., edges ‘D’ and ‘E’, was fully welded. Thus, in the analysis, the full length of edges ‘D’ and ‘E’ was fixed and constrained from moving in all directions i.e., in all of the x, y, z, translational and x, y, z, rotational directions to replicate the welded edges of the specimen in the performed experimental tests as conducted by Chung and his co-researchers (Chung et al. 2012).

TABLE 1. The mechanical properties for DOMEX 700

Source: Chung et al. (2012)

Density (kg/m^3)	Young’s modulus (GPa)	Poisson’s ratio
7850	200	0.285

TABLE 2. Johnson-Cook material properties for the V-shaped plate

Source: Chung et al. (2012)

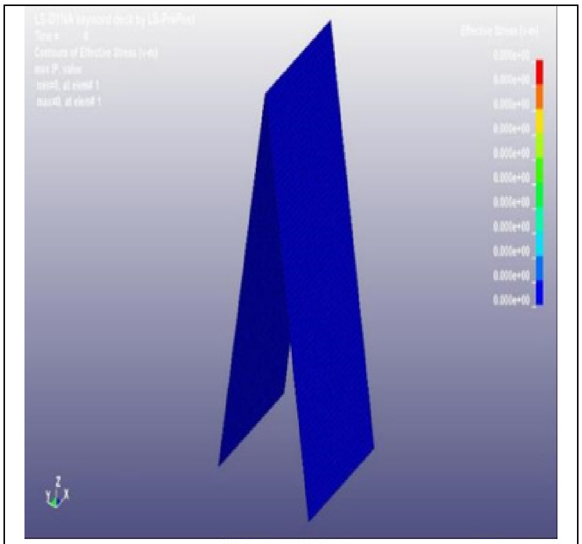
A (MPa)	B (MPa)	n	C(s^{-1})
818	1423	0.987	0.014

SOLVING THE NUMERICAL SIMULATION USING LS-DYNA

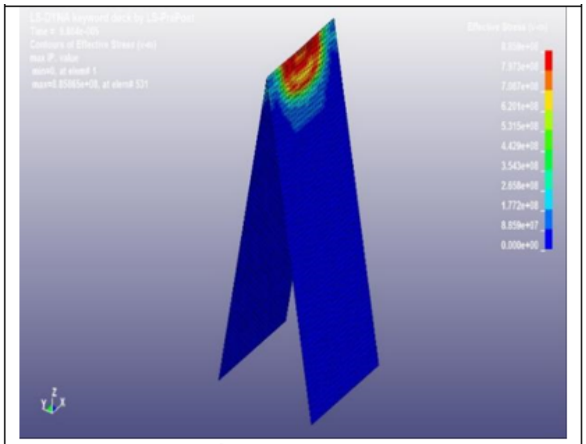
*CONTROL_TERMINATION command time of 0.5E-3 s was chosen to fully capture the whole process of the blast loading for each of the numerical simulation test case. *BINARY_DBASE_D3PLOT command with time interval between outputs of 1E-4 s was chosen to record the output data. The numerical simulation input file was then processed by using the LS-DYNA solver with hardware capabilities of Intel(R) Core(TM) i7-6820 HQ CPU @ 2.7 GHz, 16.00 GB of RAM, 64-bit Operating system, which took around 20 minutes to complete the processing of one simulation of analysis. Upon successful processing of the numerical simulation, the deflection of the V-shaped model due to the blast loading was obtained by selecting the 'Z-displacement' of the nodal mid-point displacement of the V-shaped plate model. All numerical simulation results of the mid-point deflections of the V-shaped plate models are presented in the following section.

RESULTS AND DISCUSSION

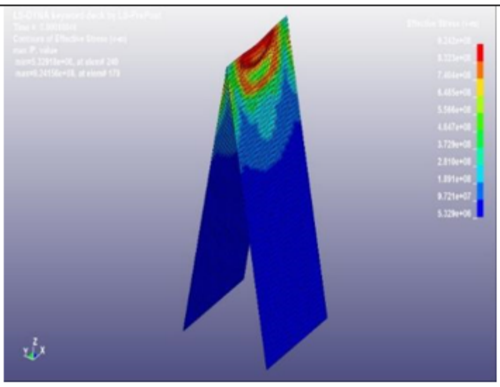
Figure 3 shows some of the stress contoured numerical simulation images experienced by the V-shaped plate due to the TNT explosion. It could be observed that at time t=0E-3 s, the V-shaped plate was in its initial condition and the TNT explosive had yet to be detonated.



Time = 0E-3s



Time = 0.988E-3s



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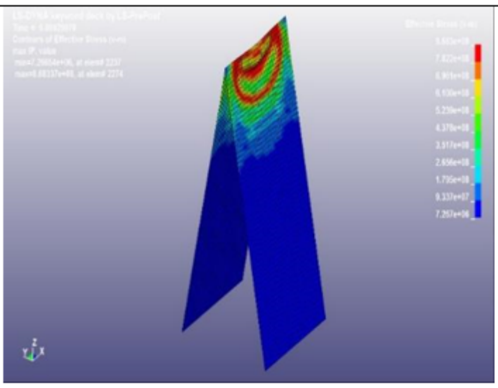

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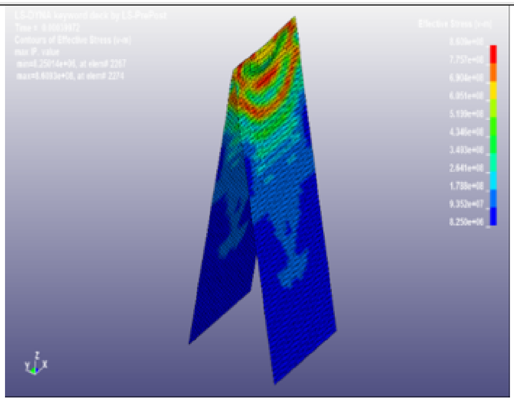

Time = 399.7E-3s

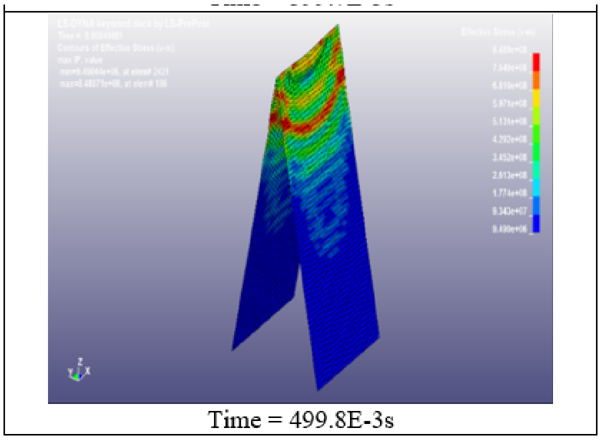

FIGURE 3. The stress contours of the V-shaped plate for Test number 'Z8', with 25 ° angle, stand-off distance of 0.03 m and 0.2 kg of TNT

At time t=0.988E-3s (see Figure 3), the TNT explosive exploded and the stress contoured zones could been seen around the vertex's top area (mid-section) of the V-shaped plate. As the explosion of TNT and time progressed, the stress contoured zones grew larger in a semi-circle patterns and noticeable deformable region can be seen at the mid-section of the V-shaped plate vertex.

Table 3 and Figure 4 show the final deflection of the mid-point vertex's magnitude of the V-shaped plate due to TNT explosions. 11 sets of numerical simulation tests were performed; starting with V-shaped plate's angle of 60 ° and gradually decreased to 10 ° with angle intervals of 5 °. The V-shaped plate angles kept decreasing, while the vertical height (defined as the vertical distance from the vertex of the V-shaped plate to the planar base of the V-shaped plate) of the V-shaped plate kept increasing with both of the mass of TNT and stand-of distance remained constant for all of the numerical simulation tests.

The numerical simulation test started with V-shaped plate's angle of 60 ° and produced a final deformation of 57.6E-3 m, which can be set as a benchmark value for comparison purposes. It could be observed that as the V-shaped plate angle decreased, the final deflection at the V-shaped plate's vertex also decreased until the V-shaped plate angle reached 25 ° (Test number 'Z8'). This showed that the optimum V-shaped plate angle was achieved which could mitigate the blast load with minimal final deflection experienced at the vertex of the V-shaped plate with the vertical V-shaped plate's height of 677E-3 m. By further reducing the V-shaped plate's angle below 25 °, the final deflection of the V-shaped plate's vertex increased progressively until it reached a final deflection magnitude of 60.9E-3 m.

The parametric studies showed that an optimum V-shaped plate angle of 25 ° had the least final deformation that implied that it could mitigate quite a large amount of the blast loading effects. At an angle of 25 °, the vertical V-shaped plate's height was 677E-3 m and defined as the vertical distance from the floor of the vehicle's undercarriage to the ground level. Alternatively, test number 'Z11', which had vertical V-shaped plate's height of 1715E-3 m (around 6 feet) with 60.9E-3 m of final deflection, may not be suitable due to the high center of gravity of the vehicle's undercarriage to the ground level and reduced stiffness due to its tendency to buckle. It could be observed that after the angle of the V-shaped plate decreased gradually from 25 ° down to 10 °, the final deformation of the V-shaped plate's vertex increased gradually.

Figure 3 shows the progressions of circular wave patterns of the effective stresses on the surfaces near the vertex of the V-shaped plate resulted from the effects of blast load of the explosive during the simulation analysis from a time period of 0E-3 s to around 500E-3 s. The original source of the circular wave patterns of the effective stresses was located at the mid top section of the V-shaped plate and it expanded away from the source in the downward directions on both sides of the plate. *LOAD_BLAST_ENHANCED command that was used in the simulation analysis only required that the user specified the x, y, z coordinates of the center point of the explosive together with its mass. During simulation, this command applied spherical explosion of pressure loads that expanded in the spherical outwards direction from the source of explosive. The spherical explosion behavior of pressure loads then hit both plates which produced progressions of circular wave patterns representing the effective stresses experienced by both plates as observed in Figure 3.

TABLE 3. Final deformation of the mid-point (vertex) of the V-shaped plates due to TNT blast loadings (with constant mass of TNT of 0.2 kg and constant stand-off distance of 30E-3 m)

Test number	Angle of V-shaped plate (°)	Vertical V-shaped plate's height (xE-3 m)	Final deflection of V-shaped plate's vertex (xE-3m)
Z1	60	260	57.6
Z2	55	288	45.2
Z3	50	322	32.0
Z4	45	362	22.6
Z5	40	412	15.0
Z6	35	476	13.8
Z7	30	560	11.8
Z8	25	677	10.5
Z9	20	851	14.2
Z10	15	1139	25.1
Z11	10	1715	60.9

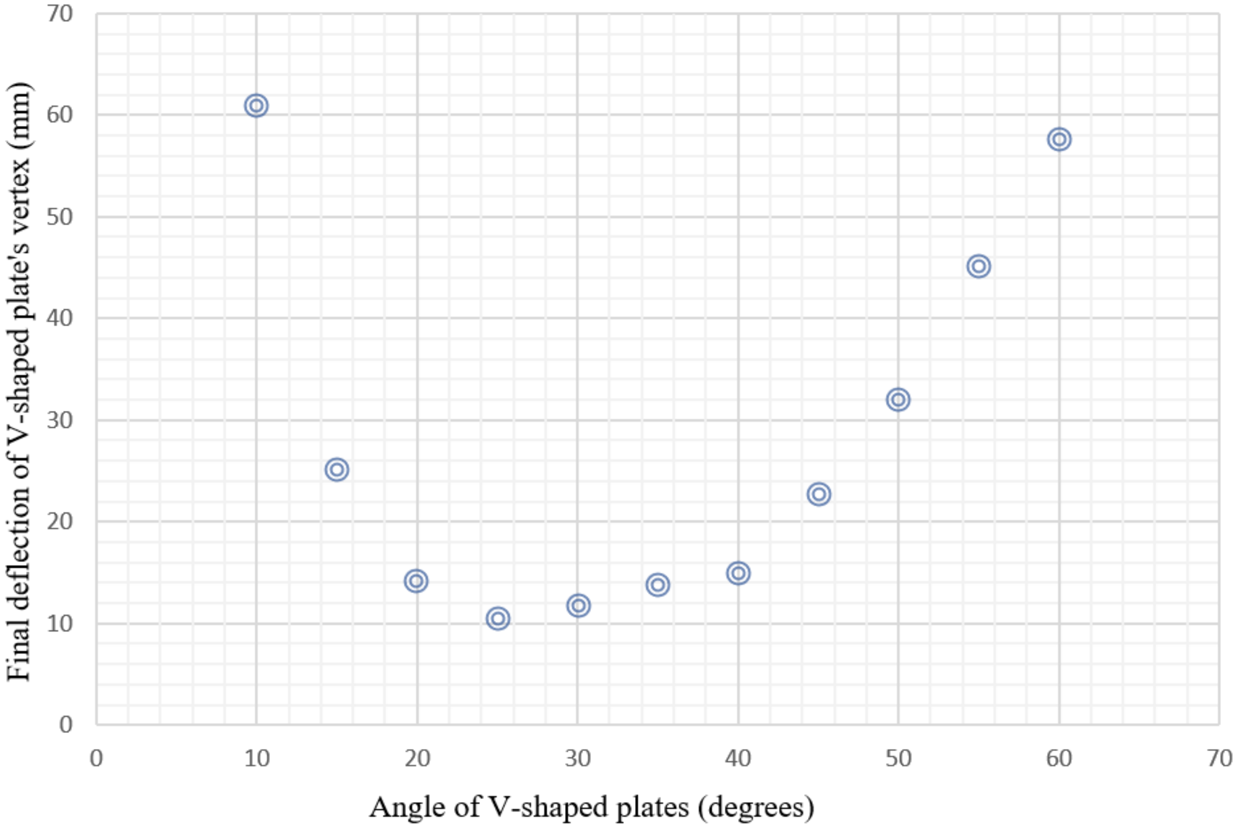

FIGURE 4. Final deformation of the mid-point (vertex) of the V-shaped plates due to TNT blast loadings (with constant mass of TNT of 0.2 kg and constant stand-off distance of 30E-3 m)

CONCLUSION

Parametric study to obtain the optimum angle of V-shaped plate to mitigate blast load by using numerical simulations i.e., LS-DYNA was performed in this paper. The investigation found that V-shaped plate angle of 25 ° gave the optimum angle with the least amount of final deformation at its vertex. Further parametric studies can be performed to obtain an overall optimum parameter of the system that would involve the mass of the explosive, the standoff distance, the V-shaped plate angle, and the thickness of the V-shaped plate.

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DECLARATION OF COMPETING INTEREST

None

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