Research paper

Effect of strength of the flyer plate material on the collision parameters in explosive welding

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Received : April 24, 2008 Accepted : March 23, 2009

Abstract

The process of oblique collision of a flyer plate on a stationary base is analyzed taking into account the strain rate sensitivity of the material of the plate. A constant angle of collision, which is very important in explosive welding, is shown to be achieved beyond critical collision parameters which are mutually connected to the dynamic behavior of the material. These critical conditions define the boundary, below which, the strength of the material affects the profile of the plate and hence the collision angle. The analytical results are supported by those of the numerical analyses as well as the hyper velocity impact experiments performed using gas gun. Based on this boundary limit and numerical analyses results, some previous experimental results are evaluated.

Keywords : Moving load, Flyer plate, Oblique collision, Explosive welding

1. Introduction

In the explosive welding a flyer plate is propelled by the sliding detonation of an explosive layer and collides on a base plate at an angle of impact (Fig. 1). The problem of acceleration of the flyer plate, within the explosive welding limits, owing to action of high compressive stresses, is usually treated using a hydrodynamic model[1)2)]. Within the hydrodynamic theory, the flyer plate is modeled as discrete incompressible fluid elements and the mechanical forces, neither in the initial bending due to action of detonation waves nor in the collision of the flyer on the base plate, do not alter the propulsion profile which is defined by the parameters, collision angle γ and collision velocity V_0. Although this approach, in the normal regimes employed in explosive welding, is quite reasonable, for a low limit of kinematical parameters of collision, the elastic−plastic properties of the flyer plate material can affect the projection profile, locally near the contact zone[3)] or entirely through the flying distance[4)]. On the other hand explosive welding of the materials which have substantially different physicomechanical properties or those that are susceptible to formation of brittle intermetallics can be best done close to these extreme parameters[4)]. In addition for obtaining a weld with uniform bonding strength, the kinematical parameters of collision should remain constant during the welding. Hence, understanding of the effects of strength of flyer plate material on the kinematical parameters under such critical conditions is of great interest. In particular it is noteworthy to deal with the problem for a rate sensitive material in which the critical velocity of collision and dynamic properties of the material are mutually connected. Deribas et al[3)]. defined a “super low limit” beyond which the collision angle γ remained constant. Below this limit the collision angle is not determined. However the analysis was presented for a rigid-perfect plastic material.

In this research, based on the concept of “superlow boundary," the effect of strain–rate sensitivity of flyer material, on the limiting boundary of the kinematical parameters of welding, below which the effects of the material strength appear, is clarified. Beyond this boundary the elastic properties of the material is exceeded and the condition of stationary and determined γ and V_0 can be achieved. The numerical analysis of the collision of a visco-plastic plate with a rigid base is also performed using a finite difference scheme[5]. Furthermore, a discussion is made on the erroneous conclusions drawn in a previous report[6] regarding the effects of strength and thickness of the flyer on the dynamic bend angle β.

2. Kinematical parameters of explosive welding

In explosive welding a plate is accelerated under a moving detonation of an explosive, and collides on a stationary base plate obliquely. Shown in Fig. 1 are a schematic plot of the process and the kinematical parameters associated with it; preset angle α, dynamic bend angle β, collision angle γ, detonation velocity D, contact point velocity V_C, and collision velocity V_0. Three of these parameters which govern the collision are connected to each other through

$$V_0 = V_C \sin(\gamma). \tag{1}$$

Considering the parallel setup ($\alpha = 0$, $V_C = D$, $\gamma = \beta$), and having D, to determine the collision parameters, it is just necessary to know the dynamic bend angle β.

Several equations have been proposed to calculate β. Based on the experimental investigations using small quantities of low detonation velocity explosives, Deribas and co–workers[7] predicted the terminal dynamic bend angle β_{max} as

$$\beta_{max} = 2\sin^{-1}\left(0.6\frac{\sqrt{1+\frac{32}{27}R}-1}{\sqrt{1+\frac{32}{27}R}+1}\right) \tag{2}$$

Here R is the loading ratio and

$$R = \frac{\rho_E \delta_E}{\rho_P \delta_P}, \tag{3}$$

where ρ is density, δ is thickness and E and P subscripts denote explosive and flyer plate.

To calculate the dynamic bend angle β at any flying distance y, measured normal to the initial plane of the flyer, the following equation was proposed[8]

$$\beta = \frac{\pi}{2}\left(\sqrt{\frac{k+1}{k-1}}-1\right)\frac{R}{R+2.71+\frac{0.184\delta_E}{y}}, \tag{4}$$

in which k is the integral polytropy index of the explosive gaseous products.

As it can be seen in these equations, for calculation of dynamic bend angle β, (and consequently collision angle γ) no account has been taken of the strength of the flyer material. However as the collision parameters go down to the critical values, the pressure level approaches values comparable to the strength of the material and the condition of stationary collision is violated near the contact zone.

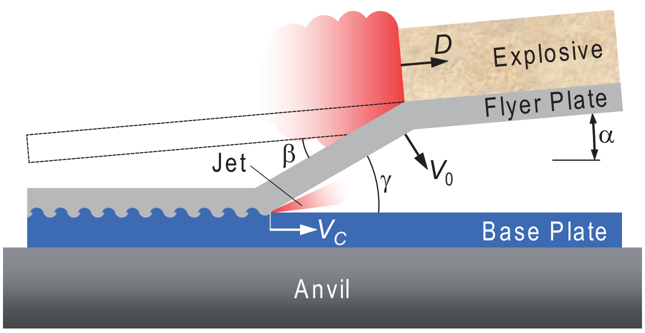


Fig. 1 Explosive welding scheme.

3. Oblique Collision of metal plates

3.1 Analysis including the effects of strain rate

The analysis of collision of the plates can be simplified for the case of symmetric collision. The symmetric collision is equivalent to the inelastic oblique collision of a metal plate on a rigid base. Deribas et al[3]. considered the conditions, under which, a rate rigid–perfect plastic plate collided on a plane at a specified stationary angle γ with a velocity V_0. In the case the collision angle remains fixed, an element of the flyer plate with a length δ_1 will be displaced by the shear force $\tau_S\delta_P$. After displacement the position of points A and B will be A' and B' respectively (Fig. 2). The work done by the shear stress τ_S during this displacement is

$$W_{Shear} = \tau_S \delta_P (\delta_1\gamma). \tag{5}$$

The initial kinetic energy E_K of this element can be found from

$$E_K = \frac{1}{2}\rho_P\delta_P\delta_1 V_0^2. \tag{6}$$

The kinetic energy of the plate is dissipated by plastic deformation energy or $W_{Shear} = E_K$, thus

$$\frac{V_0^2}{\gamma} = \frac{2\tau_S}{\rho_P}. \tag{7}$$

Let us consider the case that the strength of the plate material changes with respect to rate of deformation and the dynamic yield stress σ'_y is described by the well known Cowper–Symond constitutive equation[9]

$$\frac{\sigma'_y}{\sigma_y} = 1+\left(\frac{\dot{\varepsilon}_e}{\dot{\varepsilon}_0}\right)^{\frac{1}{q}}, \tag{8}$$

where $\dot{\varepsilon}_0$ and q are material constants, σ_y is static yield point and $\dot{\varepsilon}_e$ is the equivalent strain rate that for the simple shear deformation dealt with here one can find

$$\dot{\varepsilon}_e = \frac{\dot{\gamma}}{\sqrt{3}}. \tag{9}$$

It may be shown that

$$\dot{\gamma} = \frac{V_0}{\delta_P}. \tag{10}$$

Using (10), Eq. (8) gives the dynamic shear yield stress as

$$\tau'_S = \tau_S\left[1+\left(\frac{V_0}{\sqrt{3}\delta_p\dot{\varepsilon}_0}\right)^{\frac{1}{q}}\right]. \tag{11}$$

Replacing τ_S with τ'_S in (7) one arrives at

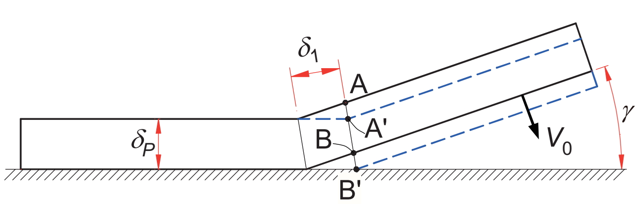


Fig. 2 Oblique collision of a plate on a rigid base.

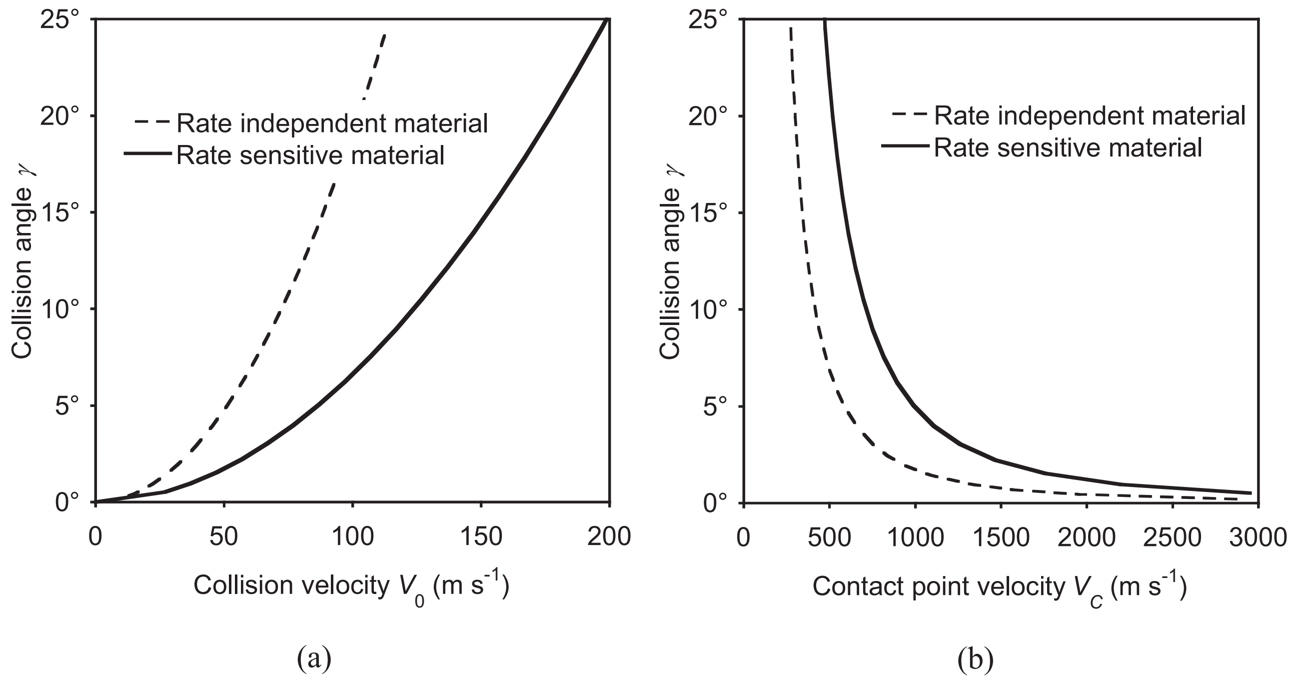


Fig. 3 The curves comparing the lower limits of kinematical parameters in (a) ; (V_0, γ) and (b) ; (V_C, γ) planes, for achieving a collision at a stationary angle γ.

Table 1 Data on stainless steel 304.

Parameter	Description	Unit	Value
ρ	Mass density	kg m^{-3}	8000
δ_P	Thickness	mm	5
σ_b	Tensile strength	MPa	500
σ_y	Tensile yield point	MPa	210
τ_S	Shear yield point	MPa	120
q	Constant in (8)[9]		10
$\dot{\varepsilon}_0$	Constant in (8)[9]		100

$$\frac{V_0^2}{\gamma}=\frac{2\tau_S}{\rho_P}\left[1+\left(\frac{V_0}{\sqrt{3}\delta_p\dot{\varepsilon}_0}\right)^{\frac{1}{q}}\right]. \tag{12}$$

Equation (12) gives the lowest amount of V_0 that is required for a viscoplastic flyer plate, which obeys Eq. (9), to collide on a rigid base at a stationary angle γ. Using (1) and rewriting (12) in the form

$$\frac{[V_C\ \sin\gamma]^2}{\gamma}=\frac{2\tau_S}{\rho_P}\left[1+\left(\frac{V_0}{\sqrt{3}\delta_p\dot{\varepsilon}_0}\right)^{\frac{1}{q}}\right]. \tag{13}$$

This lower limit can be plotted in the (V_C, γ) plane. In Fig. 3, the super low limits for a material whose properties are given in Table 1, for the cases that rate sensitivity effects are included or excluded, are compared. It can be observed that the strain rate effect displaces the super low limit to a higher position in the (V_C, γ) plane. This means that the curve approaches the lower limit of weldability window which is defined as

$$\gamma V_C = K\sqrt{\frac{H_V}{\rho}} \tag{14}$$

where HV is the Vickers hardness (in Pa) and K is a constant[10].

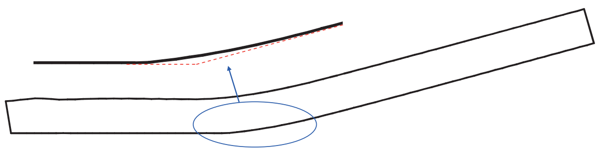
In fact, Eq. (8) has some limitations in prediction of the dynamic strength for very high strain rates involved in hypervelocity impact, however it can effectively show the behavior of the super low limit, when the effects of strain rate are included. There is little reliable information on the dynamic yield point at strain rates as high as 10^5s^{-1}. Nonetheless, calculations showed that the dynamic yield stress may reach several times the static yield point[11]. The presented analysis can suggest that the lower limit of explosive welding can be defined based on the dynamic yield point of the material.

3.2 Numerical Analysis

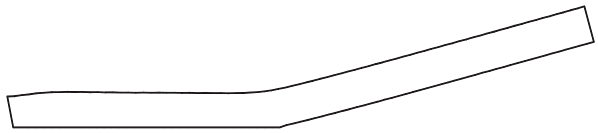
The problem of the collision of a plate on a rigid base has also been analyzed numerically, using a finite difference scheme[5]. A 5 mm thick steel plate with the properties listed in Table 1, was considered to collide on a rigid plane inclined at 15°. Runs were made with elastic plastic and elastic viscoplastic material obeying Eq. (8). Shown in Fig. 4 are the transient deformed profiles of the projectile obtained from the numerical analyses. When the material is considered to be rate independent and the velocity of the plate is V_0 = 70 m s^{-1}, it can be seen that the collision angle (near the contact point) due to the curved shape of the plate, is undetermined although that part of the plate that is in fly away from the collision zone is almost undisturbed and flies with the initial angle relative to the rigid plane. For the same material, if V_0 exceeds 90 m s^{-1} (Fig. 4(b)), the angle of collision will gain a stationary value; γ = 15° and the curved shape near the contact point can not be observed.

Now if the material behaves viscoplastically, with a collision velocity of V_0 = 120 m s^{-1}, the collision takes place at an undetermined angle. In this case when the collision velocity V_0 rises over 150 m s^{-1}, the collision angle becomes fixed and γ = 15° (Fig. 4 (d)).

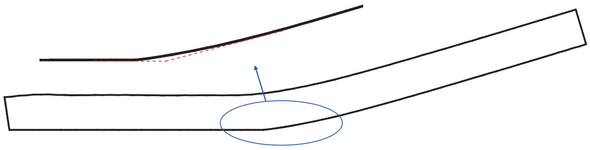
In explosive welding, for obtaining high quality welds



(a) Rate independent material, $V_0 = 70$ m s^{-1}, 120 μs.



(b) Rate independent material, $V_0 = 120$ m s^{-1}, 80 μs.



(c) Rate sensitive material, $V_0 = 120$ m s^{-1}, 80 μs.

(d) Rate sensitive material, $V_0 = 180$ m s^{-1}, 54 μs.

Fig. 4 Results of the numerical analyses for oblique collision of a stainless steel 304 plate on a rigid base.

with uniform properties along the welding direction it is important to provide the required conditions for collision at a determined and fixed angle. This criterion of stationary collision is a limit above which the strength of the material could not affect the shape of the flyer plate. To achieve welding it is necessary to increase the impact velocity even to higher values. Then it can be concluded that in the explosive welding regimes of impact, the strength of the flyer material is insignificant in determining the collision angle and the hydrodynamic approach is valid. The abovementioned condition can also define the critical parameters of explosive forming of a sheet metal in a die in which welding must be prevented.

3.3 Experimental results

Experiments have been performed on high velocity oblique collision of stainless steel 304 and titanium TP 340 to observe the deformation behavior of the flyer plate at different impact velocities. To control the velocity and angle of collision precisely, the experiments were conducted in a gas gun and the collision of the plates was observed using high speed camera. Details of the experiments can be found elsewhere[12]. Fig. 5 (a) and (b) render two snapshots of the experiments done at collision velocities of 288 and 636 m s^{-1} and collision angles of 18° and 16°, respectively.

Direct observation of the profile of the plate at the contact zone is very difficult specifically due to the formation of the metal jet. However, it may be possible to compare the profile of the two plates at the collision zone, based on the profile of the outer edge of the plate. It can be observed that the collision at relatively lower velocity of 288 m s^{-1} results in a bending type deformation of the stainless steel plate at the collision zone, while the collision at 636 m s^{-1} caused a sharp corner in the flyer near the collision zone. In these experiments, impact at 288 m s^{-1} resulted in no welding and the other sample was welded.

The experimental results show that even at a collision velocity of 288 ms^{-1} the strength of the material, significantly affects the shape of the flyer, while the numerical results predict that at this velocity the strength should be insignificant. It must be noted that in the experiments the stainless steel impacts to a non-rigid base. Then a part of the energy is spent for deformation of the base plate. Furthermore, the accuracy of the constitutive equation of the material used in the numerical analysis is not enough for such high rate of strains.

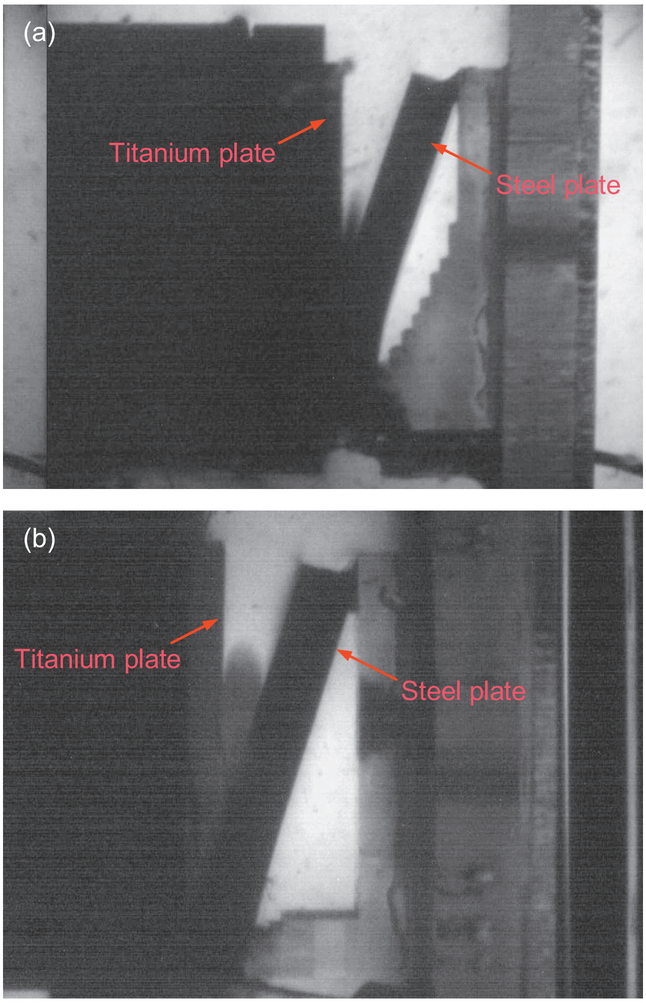


Fig. 5 Comparison between the deformation profiles of the stainless steel plates in high velocity collision on titanium plate. (a) Collision velocity = 288 m s^{-1}, (b) collision velocity = 636 m s^{-1}.

4. Discussion on the reported experimental results

Pruemmer[6] conducted explosion welding experiments, using aluminum alloy plates with various thicknesses (3–

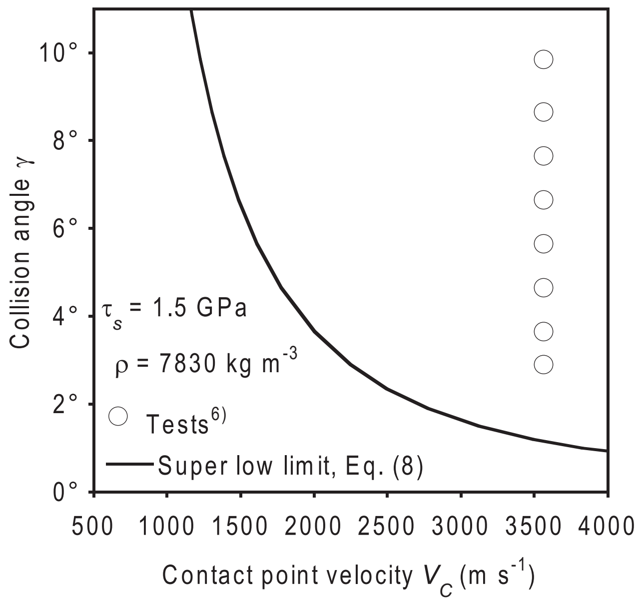


Fig. 6 Comparison of test results[6] and Eq. (13).

25 mm) as well as high strength steel plates as flyers, and compared the recorded collision angles with the predictions of Eq. (2). In those experiment parallel setup was used and hence $\gamma = \beta$. Based on the deviations observed between the experimental results and those of Eq. (2), it was concluded that the strength and thickness of the flyer plate had strong effect on explosive welding parameters. In those experiments, detonation velocity of the explosive selected (D = 3500 m s^{-1}) was high enough that even in the welding of most strong flyers tensile strength σ_b = 951 MPa), the strength of the material could not have a significant effect on the propultion profile. The reported experimental results[6] are compared with the lower limit described by Eq. (7) in Fig. 6. It could be seen that, even in the case the limiting shear stress τ_S of the material increases to 1.5 GPa due to high rate of deformation, the experimental results lie above this boundary in the (V_C, γ) plane. Thus the deviations obtained in between those experimental results and with Eq. (2), providing that the measurement method employed was enough precise, are due to the inaccuracies of the predictions of Eq. (2).

Equation (4) is known to be more accurate for estimation of dynamic bend angle β. However the properties of the explosive Am-1, used in those experiments[6], is not known for the authors to draw a comparison between those experimental results[6] and Eq. (4). Nonetheless, in this connection, the experimental results published by Besshaposhnikov et al.[9] are noteworthy. They reported that for a flyer strength range of $15 < \sigma_b < 1350$ MPa, there is no appreciable effect of the strength on the propulsion profile and having k, R, and y, the dynamic bend angle β, can be calculated precisely.

The propulsion of a plate under the action of a moving load and collision of it on a rigid base are also simulated numerically. It is assumed that the pressure pulse generated by the explosive is described by as[14]

$$P = P_0 \exp(-t/T), \tag{15}$$

where

$$P_0 = \rho_E D^2/4. \tag{16}$$

Here T is a constant that could be selected so that the resulting collision angle corresponds with the experimental records reported in reference 6). The following data were used in the numerical calculations; D = 3500 m s^{-1}, ρ_E = 1000 kg m^{-3}, σ_y = 2GPa, ρ_P = 7830 kg m^{-3} and T = 5.5 μs. Using these parameters, two runs were made for evaluation of the effects of strength (Fig. 7). In the first one (thick line), the plate collided on a rigid base at a flying distance equal to plate thickness $y = \delta_P$ = 7mm, and in the other one no collision was considered (thin line). Fig. 7 compares the transient deflection profiles obtained from these two simulations at t = 50 μs. It can be clearly seen that the collision of the plate (plastic deformation) has almost no effect on the deflection profile under this kinematical parameters.

5. Conclusions

The effects of strength of the flyer plate material on the kinematical parameters of explosive welding was analyzed, taking into account the change in the strength of the material with the deformation rate. The limiting condition of stationary collision of a rate sensitive flyer on a rigid base was clarified. Below this limit in (V_C, γ) plane, the angle of collision is affected by the strength of the flyer. The profound effect of strength on the collision angle argued previously by another paper was found to be due to misinterpretation of the experimental results. The numerical simulation of the acceleration of a plate under a moving load was also performed and no strong effect of strength on the propulsion profile was observed.

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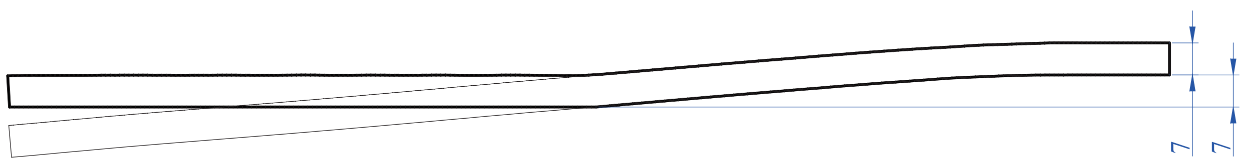

Fig. 7 Transient deflection profiles of a free (thin line) and a colliding (thick line) flyer plate obtained from numerical analysis.

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