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Impact Strength of Steel Plates Struck by Projectiles*

(Evaluation Formula for Critical Fracture Energy of Steel Plate)

by Satoshi OHTE**, Hiroyasu YOSHIKAWA**, Norimasa CHIBA***, Shigeru SHIDA***

In order to clarify the strength of structures which require leak tightness, when struck by projectiles, a series of impact tests for steel plates have been carried out. Cylindrical, semi-spherical and conical-nosed SUS304 stainless steel projectiles were impacted onto carbon steel target plates 7~38 mm thick. Test results showed that critical fracture energies of target plate by cylindrical and semi-spherical-nosed projectiles mostly agree with the values predicted by empirical formulas generally used, however, the critical fracture energy of target plate by a conical-nosed projectile is fairly smaller than these values. An evaluation formula for the critical fracture energy of target plate, applicable to three kinds of nose shaped projectiles, has been derived from the test results.

Key Words : Impact strength, Steel Plates,
Projectiles, Critical Fracture Energy, Formula

1. Introduction

The purpose of this study was to clarify the strength of structures, such as pressure vessels, which require leak tightness, when struck by projectiles which are generated as a result of fracture of an equipment near the structure.

For the steel plate impact strength, SRI formula, (1)~(5) BRL formula (5) and Jacob de Marre formula (6) are very familiar as the critical perforation energy formulas. Other critical perforation energy formulas, considering target material effects and projectile nose shape effects, are also reported. (7) However, these empirical formulas should not be applied directly to structures which require leak-tightness, because crack generation is not tolerated in these structures.

Considering these circumstances, a series of experimental studies were carried out, (8)~(10) considering crack initiation limit (later referred to as fracture limit) in target steel plates.

The previous paper (11) reported on the steel plate target thickness dependency of the critical fracture energy for 90° conical-nosed projectile, which means the critical projectile kinetic energy required to cause a fracture of the steel plate, and on the steel plate fracture condition.

This paper reports on impact tests of steel plates with use of cylindrical, semi-spherical and conical-nosed projectiles and on a new evaluation formula, applicable to these projectiles, to determine the critical fracture energy of the steel plate.

2. Materials and Test Method

Materials of the target steel plates and the projectile nose were a SGV 49 carbon steel and an austenitic stainless steel SUS 304. Mechanical properties and chemical components are shown in Table 1 and Table 2.

Table 1 Target and projectile mechanical properties.

	Yield Stress (MPa), (kgf/mm ²)	Tensile Strength (MPa), (kgf/mm ²)	Elongation (%)	Reduction of Area (%)
SGV 49	343, 35	490, 50	40	75
SUS 304	284, 29	637, 65	80	80

Table 2 Target and projectile chemical components

	C	Si	Mn	P	S	Ni	Cr
SGV 49	0.18	0.26	1.14	0.016	0.005	0.19	0.07
SUS 304	0.08	0.72	1.81	0.033	0.019	8.72	18.42

Details of the test method were described in the previous paper (11). The full size of target plate is 2 m x 2 m, but the effective size, excluding the edge part of the target to fix to the holder, is 1.5 m x 1.5 m. Projectiles are accelerated by the explosive, but combustion of the explosive has completed just before projectiles hit the target plate. Kinetic energies of the projectile were determined from measured free-flying projectile speeds.

Test conditions are shown in Table 3. Target plate thicknesses are 7 ~ 38 mm. Projectile nose shapes are cylindrical, semi-spherical and 90° ~ 20° conical.

Shape effects of projectile nose on the critical fracture energy of the target plate were investigated from the tests of the 7 mm thick plates. Target thickness effects on

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** Toshiba R and D Center, Toshiba Corporation (Ukishima-cho 4-1, Kawasaki-shi, Japan).

*** Mechanical Engineering Lab., Hitachi Ltd. (Saiwai-cho, Hitachi-shi, Ibaraki, Japan)

Table 3 Test conditions

Target Thickness (mm)	Projectile			
	Nose Shape	Diameter (mm)	Mass (kg)	Velocity (m/s)
7		87.5	3~18	25~170
10		66~160	3~50	50~180
20		66~160	3~50	50~150
30		66~160	4~50	60~150
38		99~160	24~45	93~142

the critical fracture energy were investigated from test with 90° and 40° conical-nosed projectiles.

Nose angle effects of conical projectile were also investigated from the test of the 20 mm thick plates.

3. Test Results

Test results on 7 mm thick targets, with use of cylindrical, semi-spherical and conical-nosed projectiles, are shown in Fig. 1.

Fig. 1 Test results on 7 mm thick target plates.

Test results have been classified according to the target failure mode. The following symbols are used in the figures in this paper.

- × : Perforation (Projectile passed through target)
- Δ : Fracture (Cracks or a small hole observed)
- : No Failure (Only plastic deformation, without cracks)

Critical perforation energies of the target calculated by Stanford Institute Formula, Jacob de Marre Formula and BRL Formula, are also shown in Fig. 1.

Target failure modes in the tests with cylindrical projectiles were perforation and no failure. In this case, the critical perforation energy is mostly in good agreement with those predicted by three old formulas.

Target failure mode in the tests with semi-spherical-nosed projectiles showed no failure. Figure 1 shows that the critical energy for the case of semi-spherical-nosed projectile is almost the same magnitude as,

or larger than, that of cylindrical projectiles.

On the contrary conical-nosed projectile tests indicate that perforation or fracture occurred even with smaller projectile energy than those estimated by these formulas.

Photographs of the steel plates struck by the cylindrical and 90° conical-nosed

(a) Perforated by a cylindrical-nosed projectile.

(b) Fractured by a 90° conical-nosed projectile.

(c) Perforated by a 90° conical-nosed projectile.

Fig. 2 Target failure mode (7 mm thick target plates).

projectiles are shown in Fig. 2. In case of cylindrical-nosed projectile, the plate was punched out by shear mode (Fig. 2(a)). In case of conical-nosed projectile, crack generation (Fig. 2(b)) and perforation as a result of crack extension (Fig. 2(c)) were observed.

As mentioned above, it is clear that the critical energy of the target remarkably depends on projectile nose shapes.

Test results for the case of 90° and 40° conical-nosed projectiles are shown in Fig. 3.

Fig. 3 Test results obtained using 90° and 40° conical-nosed projectiles (critical fracture energy dependency on target thickness).

Symbol ● in Fig. 3(b) denotes the critical fracture energy of a 7 mm thick target, estimated by the simplified model analysis.⁽⁸⁾ This value is in good agreement with that estimated by the extrapolation of the test results of 20~38 mm thick target shown in the figure.

The previous paper stated that the critical fracture energy, E_f , for the case of 90° conical-nosed projectile, can be expressed by Eq. (1)

$$E_f \propto T^3 \quad (T: \text{Target thickness}) \quad (1)$$

It is clear from Fig. 3(b) that the critical fracture energy for the case of 40° conical-

nosed projectile can also be expressed by Eq. (1).

Test results on 20 mm thick targets are shown in Fig. 4. The critical fracture energy markedly depends on the nose angle of the conical projectile.

Fig. 4 Test results on 20 mm thick target plates (critical fracture energy dependency on conical projectile nose angle).

4. Discussion

In this article some discussions are presented on the failure modes of target and the deformation modes of the projectile. Furthermore a new empirical formula for the target fracture has been derived from above discussion.

4.1 Target Failure Modes and Projectile Deformation

Deformation of the plates caused by projectiles with variously shaped noses are shown in Fig. 5. Characteristics are sum-

Fig. 5 Target deformation modes by projectiles with various nose shapes.

marized as follows.

Cylindrical-nosed projectile: An initial crack in the target plate is generated around a contacting area between the target and the projectile of diameter D_m . The target is perforated at the same time as an initial crack is generated. Therefore, the formerly defined "Fracture Mode" is not observed.

Conical-nosed projectile: A nose tip of a conical projectile is deformed to an almost flat shape with diameter, d_1 , by compressive impact force. An initial crack in the target plate is generated around a

contacting area between the target and flat shape diameter d_1 . In addition, secondary cracks are generated radially as the projectile travels forward, pushing the target with the base of the conical head. Cracks shown in Figs. 2(b) and (c) are secondary cracks. The total contacting area, with diameter d_2 , between the target and the base of the conical projectile head, depends on the nose angle of the conical projectile.

The maximum residual deflection in no-fracture targets, W , and the flat shape diameter, d_1 , are plotted against projectile

Fig. 6 Maximum residual deflection in target, W , subjected to conical-nosed projectile impact, and flat diameter, d_1 .

energy in Fig. 6. Although W increases proportionally to projectile energy, d_1 shows a nearly constant value. From these data, it is assumed that the nose tip of a conical-nosed projectile is deformed to a flat shape in a short time at collision. After that, the target continues to deform until a crack is generated.

It is reasonable to think that, as the flat shape diameter, d_1 , is the most important factor for the target fracture, the critical fracture energy for the case of conical-nosed projectile can be expressed as an equation similar to that for usual critical perforation energy for the cylindrical-nosed projectile. In this case, the effect of total contacting area between the target and conical projectile seat should be considered.

Figure 7 shows thickness dependencies upon d_1 and d_2 . In a series of tests, in

Fig. 7 Diameters d_1 and d_2 in conical-nosed projectiles, after tests under nearly critical condition. (Nose angle $\theta = 90^\circ, 40^\circ, 30^\circ$).

which targets with constant thickness and projectiles with constant nose shape were used, some test results were classified as no-fracture. A test using the maximum projectile energy in no-fracture tests was re-

ferred to the test under the nearly critical condition. The data shown in Fig. 7 have been measured from tests under the nearly critical condition. The figure shows that d_1 has almost the same value as that of target thickness, T , independently of the nose angle θ of conical projectile. Meanwhile, d_2 increases proportionally to T , depending on θ .

4.2 Evaluation Formula for Critical Fracture Energy

Figure 8 shows the residual deflections of the targets tested under the nearly

Fig. 8 Residual deflections in targets after tests under nearly critical condition.

critical condition. The residual deflection markedly depends on projectile nose shape and target thickness.

In the evaluation formulas, which have been obtained in many studies, the perforation limit of steel plates against cylindrical or parabolic-nosed projectiles, is generally expressed as a function of projectile diameter D_m and target thickness T .

In this study, critical fracture energies of steel plates for the conical-nosed projectiles were assumed to be expressed by a similar formula to general perforation formulas for the cylindrical-nosed projectiles, because the nose tip of a conical-nosed projectile is deformed to a flat shape in a short time at a collision. Here, the critical fracture energy of the steel plate, E_f , was assumed to be expressed by Eq. (2), similarly to BRL formula or Jacob de Marre formula.

$$E_f = a D_e^\alpha T^\beta \quad (2)$$

where, a , α and β are constants. D_e is a projectile equivalent diameter, which equals to D_m in the case of cylindrical-nosed projectiles.

$$D_e = D_m \quad (3)$$

In the case of conical-nosed projectile, the equivalent diameter D_e is thought to be as follows. It is assumed to be expressed by Eq. (4), which is a combination

of a term representing the effect of a flat shape diameter d_1 (independent of conical projectile nose angle θ), and a term which represents the effect of the total contact area diameter d_2 (dependent on θ).

$$D_e = d(T) + K(T, \theta) \quad (4)$$

As the diameters d_1 and d_2 increase proportionally to the target thickness T , as is seen in Fig. 7, Eq. (4) becomes Eq. (5).

$$D_e = bT + K'(\theta) \cdot T \quad (5)$$

The second term represents the effect of an area where the target and the projectile contact each other with its conical seat, as denoted by d_2 . It becomes zero when θ is zero and increase with θ . So, the following equation was adopted as an equivalent diameter.

$$D_e = bT + c\left(\tan \frac{\theta}{2}\right)^\gamma T \quad (6)$$

where, b , c , γ are constants. As a diameter d_1 is nearly equal to the target thickness T , as shown in Fig. 7, the constant b assumes the following value.

$$b = 1.0 \quad (7)$$

As the value for an index α of Eq. (2), into which Eq. (6) or Eq. (3) is substituted, the value in Eq. (8) was selected for the following reason.

$$\alpha = 1.5 \quad (8)$$

Figure 9 shows the reason for selecting Eq. (8). In the figure, test results of 7 mm

Fig. 9 Critical fracture energy dependency on projectile's equivalent diameter.

thick targets using cylindrical-nosed projectiles are plotted against an actual projectile diameter, using symbols $\times$ and $\circ$ (same meaning as for Fig. 1). The critical fracture energy of the same thick target by a 40° conical-nosed projectile, estimated from Fig. 3(b), is plotted against an equivalent diameter, using symbol $\bullet$. In the case of 40° conical-nosed projectile, the difference between diameters d_1 and d_2 is very small. Both diameters are nearly equal to the target thickness T . Consequently, the effect of an area where the target contacts a conical seat of projectile seems to be negligible. Then, considering that the second term in Eq. (6) is negligible compared to the first term, the estimated critical fracture energy for 40° conical-nosed pro-

tile is plotted against $D_e = 7$ mm in Fig. 9. The dotted line in the figure shows that the critical fracture energy increases proportionally to the 1.5-th power of equivalent diameter D_e . For this reason, the value in Eq. (8) was adopted.

Substituting Eq. (6) with $\alpha = 1.5$ into Eq. (2), and considering experimental results in Eq. (1), the following equation is obtained.

$$\beta = 1.5 \quad (9)$$

Equation (2) with $\alpha = 1.5$ and $\beta = 1.5$ corresponds to BRL formula, formerly mentioned empirical critical perforation formula.

The other unknown constant in Eq. (2), α , can be determined from the critical fracture energy data of 7 mm thick target by cylindrical-nosed projectile, shown in Fig. 1. Then, Eq. (2) becomes Eq. (10).

$$E_f = 3.0 \times 10^8 T^{1.5} D_e^{1.5} \quad (10)$$

Unknown constants in Eq. (6), c , γ can be determined from the critical fracture energy data on a 90° conical-nosed projectile and that on a 40° conical-nosed projectile, shown in Fig. 2. Then, Eq. (6) becomes Eq. (11)

$$D_e = T \left\{ 1 + 2.9 \left(\tan \frac{\theta}{2} \right)^{2.1} \right\} \quad (11)$$

where, dimensions of D_e , T , E_f are (m), (m), (kgf·m), respectively.

Critical fracture energies calculated from Equations (10) and (11) are shown by the solid lines in Figures 3 and 4. It is clear that these equations can closely represent the test results.

Figure 10 shows the equivalent diameter D_e calculated from Eq. (11) with the change

Fig. 10 Equivalent diameter dependency on conical projectile nose angle.

of nose angle θ . As D_e increases with θ , the assumption in Eq. (12) is acceptable for the application of these formulas to both cylindrical and conical-nosed projectiles without contradiction with usual empirical formulas. Because, if θ becomes sufficiently large for the whole conical seat of projectile to contact a target plate, an initial crack is expected to be generated around the whole contact area.

$$D_e = D_m \quad (\text{If } D_e > D_m) \quad (12)$$

The critical fracture energy for a semi-spherical-nosed projectile seems to be

the same as, or larger than, that for a cylindrical-nosed projectile. Consequently, Eq. (3) is also acceptable for a semi-spherical-nosed projectile.

A tip of conical-nosed projectile was deformed to a flat shape, whose diameter d_1 showed almost the same value as the target thickness. In the case of cylindrical-nosed projectile whose diameter D_m is smaller than the target thickness T , the projectile itself seems to be deformed or fractured. Accordingly, Eq. (3) is effective, when D_e is larger than T .

Additionally, the evaluation formula for steel plate fracture, derived from this study, is applicable to the evaluation of SGV49 steel plate struck by SUS304 steel projectile under the following conditions.

Projectile Velocity V : $V = 25 \sim 180$ m/s

Target Size (length of size L):

$$L/T \geq 1500/38 = 39$$

5. Conclusions

The following conclusions have been obtained from a series of tests for evaluating the impact strength of SGV49 carbon steel plates 7~38 mm thick impacted by the cylindrical, semi-spherical and conical-nosed SUS304 stainless steel projectiles.

(1) The deformation and fracture modes of steel plates differ according to the projectile's nose shape.

(2) Both the critical fracture energy of the steel plate for a cylindrical-nosed projectile and that for a semi-spherical-nosed projectile mostly agree with the values predicted by empirical formulas generally used.

(3) The critical fracture energy for a conical-nosed projectile is fairly smaller than the values predicted by empirical formulas.

(4) The following evaluation formula for the critical fracture energy E_f (kgf·m), applicable to cylindrical, semi-spherical and conical-nosed projectiles, is obtained.

$$E_f = 3.0 \times 10^8 T^{1.5} D_e^{1.5}$$

$$D_e = T \{ 1 + 2.9 (\tan \frac{\theta}{2})^{2.1} \} : \text{for conical-nosed projectiles}$$

$$D_e = D_m : \text{for cylindrical, semi-spherical and conical-nosed } (D_e > D_m) \text{ projectiles.}$$

where

T : target plate thickness, m

D_m : projectile diameter, m

θ : nose angle for conical-nosed projectile

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