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Shear failure of a steel member due to a blast

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Abstract

Attention is focused on the failure mode of a steel brace in New York World Trade Center, which was partly exploded in 1993. Theoretical behavior of a rigid–plastic beam under blast-type loading is reviewed from a literature. It is indicated that shearing action plays an important role in such a case of blast loading, both from observation and theoretical modeling. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Blast loading; Plastic response; Failure mode; Shear force; Steel bar; Explosion

1. Introduction

The violent explosion of a terrorist's bomb ripped through a parking garage in a sublevel of New York City's World Trade Center complex (WTC) on February 26, 1993. Six people were immediately killed and more than a thousand injured. The explosion caused extensive damage in several other sublevels; fire spread smoke throughout the sublevel and into four buildings, resulting in serious problems against the occupants. This paper presents a study of failure mode for structural members under blast loading with emphasis on a steel brace. Considering that shearing action plays an important role in impulsive loading from a theoretical point of view, an attempt is made to correlate to a practical fact in this event. Plastic response of a beam to blast loading is reviewed from literature for comparison. It is preceded by a brief summary of the building layout and structural damage at WTC.

2. Background

First occupied in December 1970, WTC consists of seven high-rise buildings. Fig. 1 shows six of them, which were constructed on top of a 16-plus acre, six-level base structure. Towers 1 and 2 are 110-story office buildings that rise to a height of 1350 ft, the second tallest in the world at that time; each floor covers approximately 1 acre. Vista Hotel has 22 stories. A 5-acre open-air Plaza

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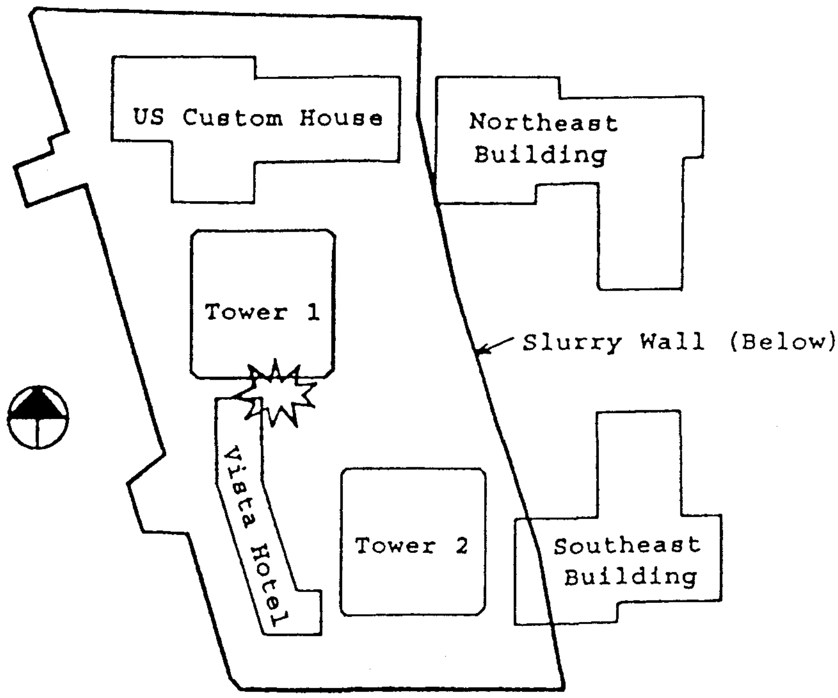

Fig. 1. Plan view of the World Trade Center Complex.

surrounds these buildings. The Concourse is the first level below the Plaza. Below the Concourse are six sublevels, Levels B1–B6. The part of the B2 level under Towers 1 and 2, the Vista Hotel, and the Customs House contains parking and utility areas.

All of the floor framing both inside and outside the footprint of the Towers is carried on steel wide-flange columns. The Plaza and Concourse levels consist of concrete slabs on profiled metal deck, composite with steel beams and girders. The B1–B5 levels below are typically 11 in thick concrete flat slabs with 4 in deep drop panels. Steel shear heads connect the concrete flat slab construction to the steel columns. The thick B1 and B2 slabs act as horizontal diaphragms, providing two levels of bracing for the 6-story high slurry wall that surrounds the WTC site.

3. Structural damage

The explosion occurred on the B2 level of the complex, centered on a vehicle ramp below the Vista Hotel adjacent to the Tower 1 (Fig. 1). The blast force tore holes in three reinforced-concrete slabs, leaving columns standing without lateral support for more than 50 ft in places. There is a 22 × 18-ft hole on the Concourse level outside the Vista tower footprint; an 80 × 50-ft hole on B1; and a 130 × 120-ft hole on B2, as shown in Fig. 2. The blast also ripped out a Tower 1 perimeter brace, as shown in Fig. 3, and Photos 1–3. This was a two-piece steel diagonal weighing about 3100 pounds and located just a few feet from the blast. Half was thrown about 40 ft into the Tower, while the other half rebounded into the holes. An adjacent diagonal was bent extensively; the upper end of its 1-1/4 in thick plate was sheared off its connection to the columns.

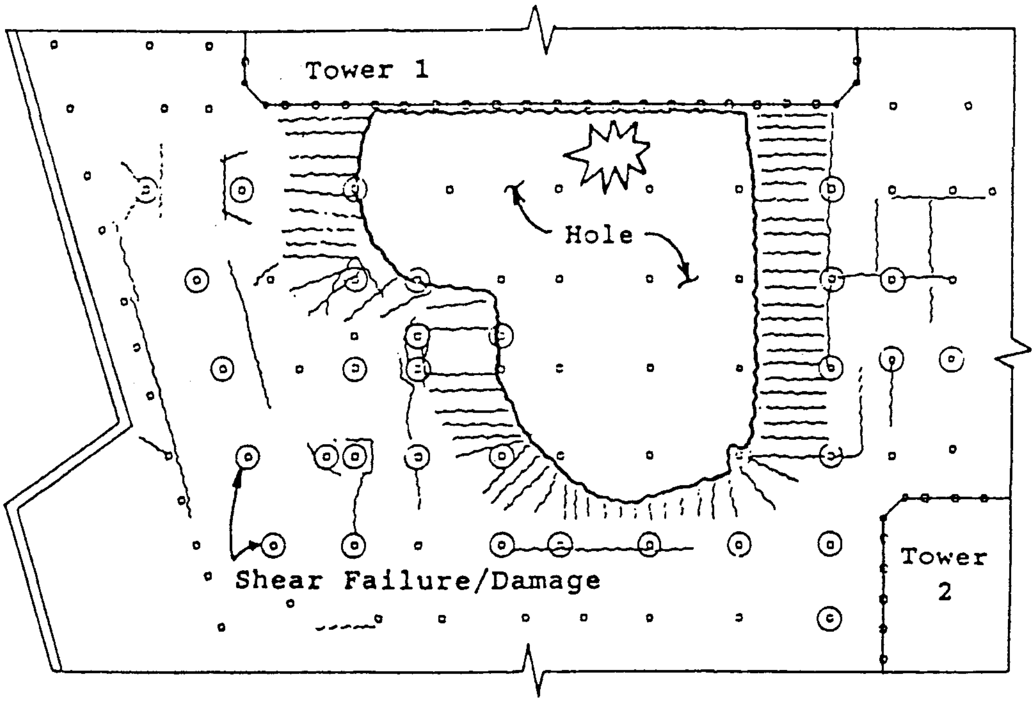

Fig. 2. Damage at the B2 level.

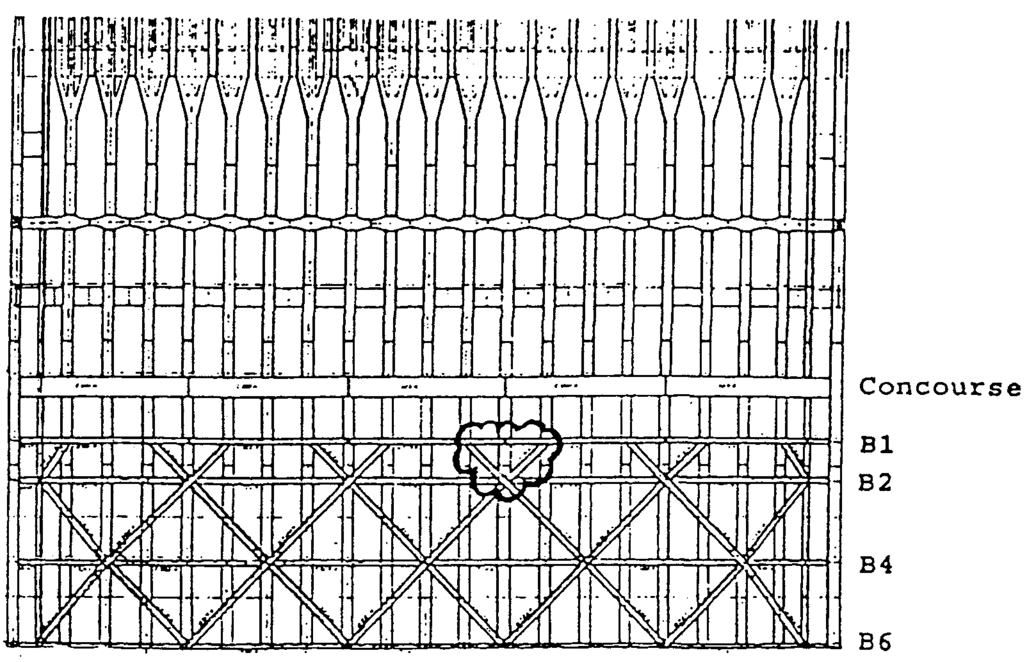

Fig. 3. South elevation of Tower 1, indicating damaged area.

There were other damages to non-structural constituents, such as to block partition walls. The minor localized structural damage did not affect the overall structural integrity of the Towers, but their structural skeleton was sufficient to overcome the intensity of the blast. The failure mode of the torn brace is worth noting. It is seen from the photos that this brace must have undergone

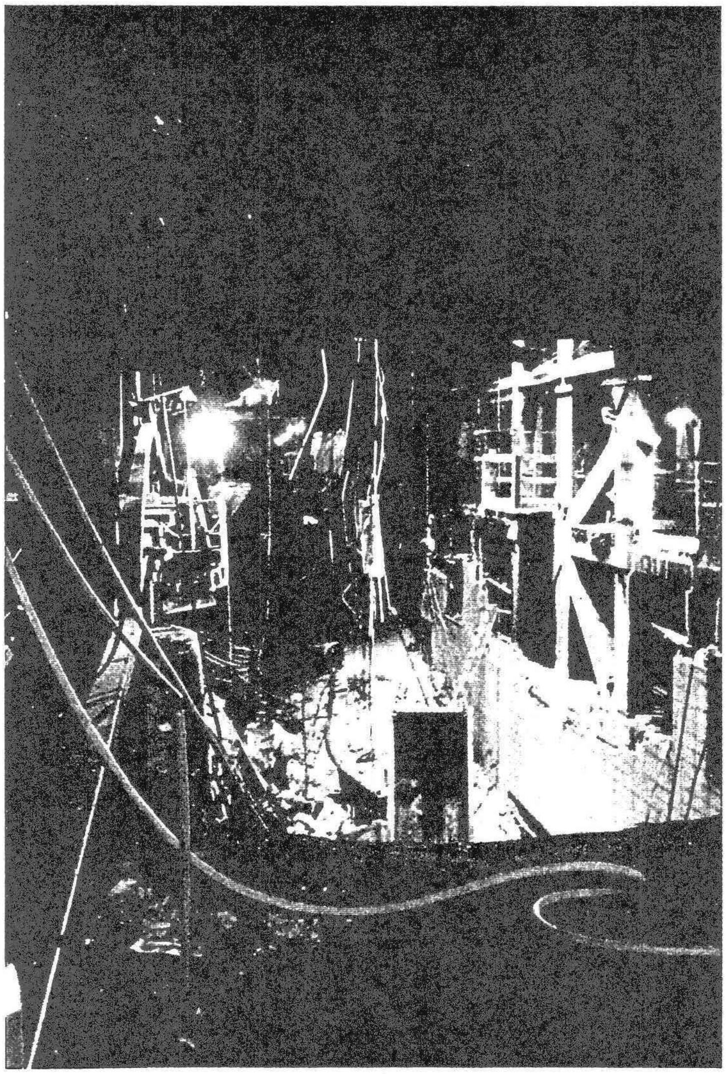

Photo 1. Site of explosion, looking toward the south wall of Tower 1. Note the missing top-left diagonal brace.

severe shearing, in addition to bending action, near the end sections due to the transverse blast force.

4. Plastic response of beam to blast

It is true that bending action predominates in long beams under normal conditions of transverse loading, but there are certain situations where shearing action plays an important role. The shear effect is significant in the case of blast loading, which involves large intensity of load in comparison with the load carrying capacity in shear [1–4]. For the purpose of later comparison, theoretical results are cited below from a closed-form solution for a simply supported rigid–perfectly plastic beam under blast-type loading [2].

It is assumed that the total load is distributed uniformly along the beam span of length $2l$, and that the load intensity decreases monotonically in time, starting with peak value P_0. In-plane

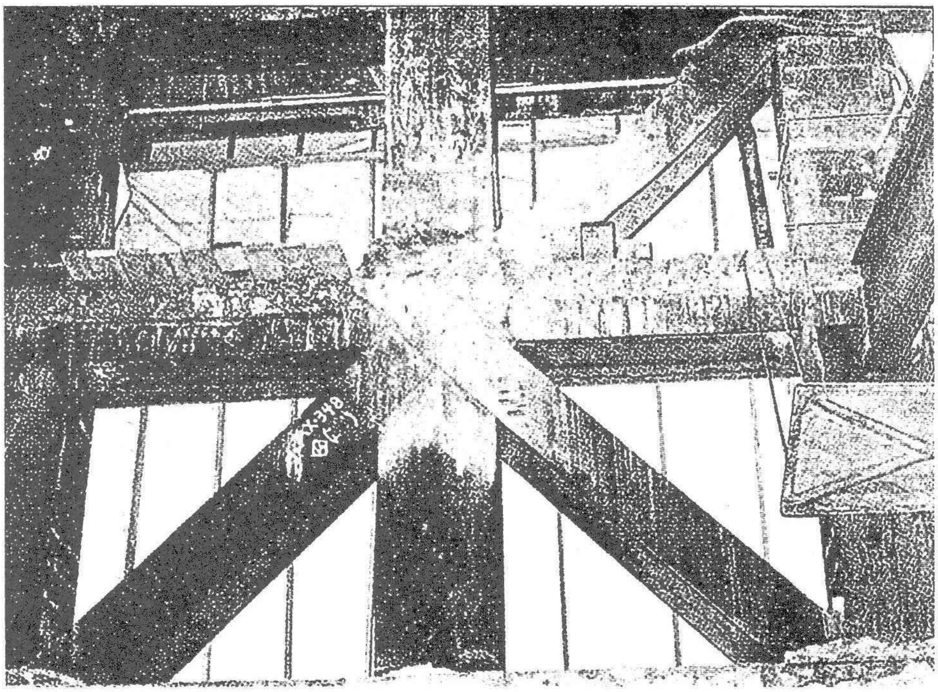

Photo 2. Close-up view of the bracing system (from [8]).

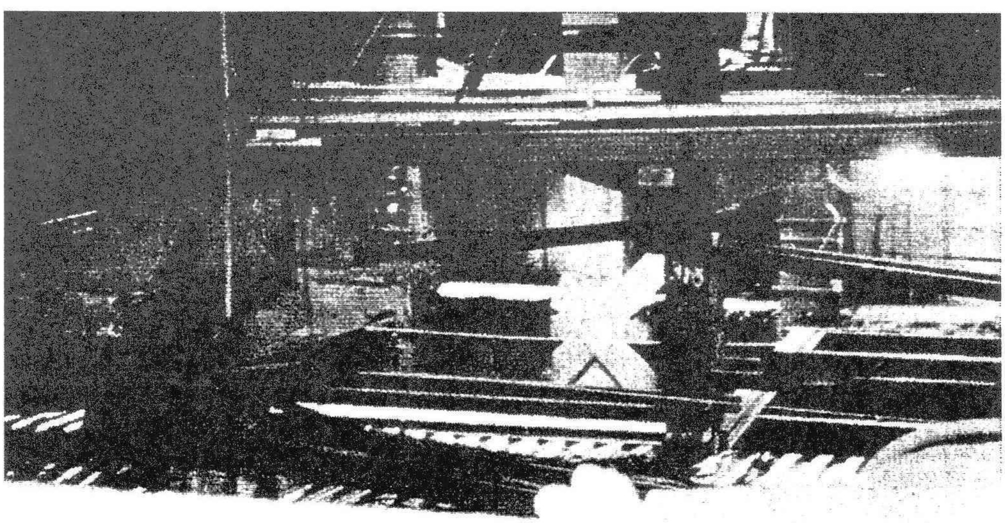

Photo 3. Under repairing. See the end of the sheared-off diagonal brace, as well as the stripped bracket on the left.

motion starts with various combinations of shear sliding and bending deformation, depending upon the relative magnitude $\mu_o = P_o/P_b$ of P_o to the plastic collapse load $P_b = 4M_o/l$ in bending, and upon the ratio $v = P_s/P_b$ of the shear capacity $P_s = 2Q_o$ to P_b , where M_o and Q_o are the fully plastic bending moment and shearing force of the beam section, respectively.

The impulsive loading, $\mu_o \to \infty$, converts the blasting energy into kinetic energy $I^2/(4\,ml)$, which is absorbed by plastic deformations, and hence equals the sum of plastic work in bending E_b and

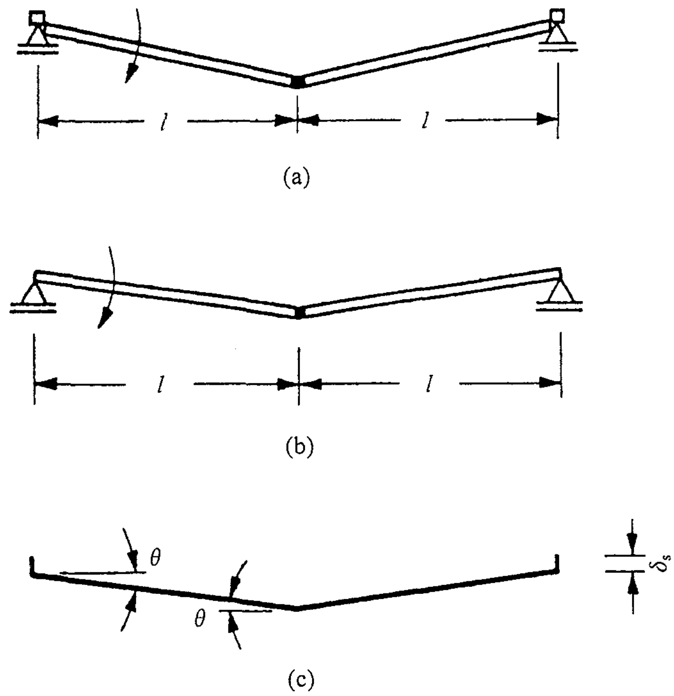

Fig. 4. Rigid-plastic beam under blast-type loading for $1 \leqslant \nu \leqslant 3/2$. (a) First phase of motion. (b) Second phase of motion. (c) Residual deformation.

plastic work in shear E_s , where I is the total impulse, and m is mass per unit length. The energy ratio E_b/E_s increases monotonically with increasing ν. If $1 \leqslant \nu \leqslant 3/2$, in particular, then the motion starts with shear sliding at the both ends together with a plastic hinge at the center, as shown in Fig. 4(a). The sliding terminates first, and the motion changes into a pattern of ordinary collapse in plastic bending, as shown in Fig. 4(b). As shown in Fig. 4(c), the final deformation contains shear deformation δ_s and slope angle θ, given by

$$\delta_s = \frac{1}{16(4\nu - 3)} \frac{I^2}{mM_o}, \tag{1}$$

$$\theta = \frac{3}{8} \frac{\nu - 1}{4\nu - 3} \frac{I^2}{mlM_o}. \tag{2}$$

The relative importance of shearing to bending is represented by the ratio

$$\frac{E_s}{E_b} = \frac{2Q_o\delta_s}{2M_o\theta} = \frac{\nu}{3(\nu - 1)}. \tag{3}$$

5. Remarks

The torn steel brace at WTC must have undergone plastic deformation due to blast loading, to such an amount that exceeds its ductility capacity. Judging from the photos, it appears that the end sections have suffered extensive shearing deformation, causing final rupture. In order to investigate this possibility, an estimation is made of the energy ratio from Eq. (3), by assuming drastically that the brace can be replaced by the model described above. The idealization of simple support does not reflect the actual boundary condition. If the ends were completely fixed, $P_b = 8M_o/l$, viz., the collapse load would be doubled. Since P_s would be unchanged, μ_o and v would be one half of their respective values in the case of the simply supported beam. Considering that these are the possible extremes, the error due to the assumed boundary condition may be conjectured to remain within a factor of two. A very rough approximation is made just to give order of magnitude, because details are unknown. A wide flange section is assumed such that two flanges with thickness t_f and breadth b are separated by a distance h through a web of thickness t_w, and is loaded in the plane of the web. By writing yield stresses in tension and in shear as σ_o and τ_o, respectively, $Q_o \cong \tau_o t_w h$, $M_o \cong \sigma_o t_f\, bh$. It follows that

$$v = \frac{Q_o l}{2M_o} \cong \frac{\tau_o}{2\sigma_o} \frac{t_w l}{t_f\, b}. \tag{4}$$

If the maximum pressure p is generated uniformly over a surface S to give the peak load $P_o = pS$, then

$$\mu_o = \frac{P_o l}{4M_o} \cong \frac{pSl}{4\sigma_o t_f\, bh}. \tag{5}$$

A previous investigation for the amount of the explosive just sufficient to make a hole in the afore-described concrete slabs gives a lower-bound estimation of 136 kg (see Appendix A). The assumption that 500 kg explosive was detonated at a distance 1 m from the brace leads to $p = 437.5\ \text{kgf/cm}^2$, according to a result of past experiments (see Appendix B). Further assumptions that $S \cong 10\ \text{m}^2$, $l \cong 3\ \text{m}$, $\sigma_o \cong 2400\ \text{kgf/cm}^2$, $t_f = (11/8)\ \text{in} = 3.493\ \text{cm}$, $b = 18\ \text{in} = 45.72\ \text{cm}$ and $h = (2 \times 12 + 11/8)\ \text{in} = 64.45\ \text{cm}$ are substituted into Eq. (5), to give $\mu_o = 132.9$. This validates the idealization that the blast load was applied impulsively. Assigning the ratio $\sigma_o/\tau_o = \sqrt{3}$ in addition to $t_w = (3/4)\ \text{in} = 1.905\ \text{cm}$ in Eq. (4) results in $v = 1.033$. It follows from Eq. (3) that $E_s/E_b = 10.37$. This result indicates that the energy absorbed by plastic shearing is of magnitude one order higher than that by plastic bending. A word of caution may be in order. The energy ratio is markedly sensitive to the value of v, when v is close to unity. Granted that the approximations made above are too rough to derive quantitative outcomes, validity remains perhaps as to the order of magnitude. It is concluded thus that although the brace must have been broken into two by plastic bending near the center, the end portions may have been ruptured largely due to shearing.

Appendix A. Blast on concrete slabs

Among past studies on damage of concrete structures due to explosion, an empirical formula has been derived for a minimum thickness necessary to resist blast without a hole being torn in a concrete slab. A number of tests were carried out in free air resulting in the equation

$$\frac{t}{\sqrt[3]{W}} = 3.80\left(\frac{\sqrt[3]{W}}{D}\right)^{2/3}, \tag{A.1}$$

where t is the required thickness in cm, and D is the stand-off in m, and W is the amount of the explosive charge in kg [5]. No specification is made as to the kind of explosive and the amount of reinforcement in the slab. This has a fair agreement with Brode's solution [5,6].

The floor slab of B1 level at WTC site had the thickness of $t = 11$ in $= 27.94$ cm. Considering that the explosion occurred on B2 level, and that the story height between the B2 and B1 level was 10 ft $= 3.048$ m, it is taken that $D = 3.00$ m in this equation to estimate a lower bound:

$$W \geqslant \left(\frac{tD^{2/3}}{3.80}\right)^{9/5} = 136\ (\mathrm{kg}). \tag{A.2}$$

It was widely reported in various publications that at least 1000 lb of explosive was set in an automobile vehicle. This together with Eq. (A.2) has lead to the assumption of the 500 kg explosive.

Appendix B. Blast pressure

Blast produced by explosion rises immediately to a peak and decreases monotonically with time. It is known experimentally that the peak pressure p (kgf/cm^2) is a function of the scaled distance $D/\sqrt[3]{W}$, based on the principle of cube root scaling. The following formula has been derived from easurement by a blast meter:

$$\log p = -1.575 \log \frac{D}{\sqrt[3]{W}} + 1.224, \tag{B.1}$$

where W is the amount of Sinkiri dynamite in kg [7]. By comparing energy produced, the amount of standard TNT dynamite equivalent to Sinkiri is given by multiplying the factor $1239/1950 = 0.635$. Substitution of $D = 1$ and $W = 500 \times 0.635$ into Eq. (B.1) gives $p = 437.5$, as evaluated in the text.

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