Research paper

Empirical equation to predict the deformation of a steel pipe under an internal blast load

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Abstract

A series of internal blast loading tests on steel pipes have been conducted. The specimens are Japanese Industrial standards with ratio of length to diameter of one. On the basis of experimental results we found on an empirical relation between the deformation and the scaled distance, which is the pipe radius divided by the 1/3rd power of the amount of explosive. The empirical equation was formulated from the experimental results and was also evaluated using both experimental results and numerical simulations. The proposed equation can predict the amount of strain or deformation for an arbitrary amount of explosive and size of steel pipe.

Keywords : steel pipe deformation, blast load, scaling law

1. Introduction

We have developed a blast containment container as a countermeasure against terrorism. The aim of this study is to develop a container with a compact size that can contain the blast of a 10 kg TNT explosion. The container consists of an outer container and an internal structure. If the internal structure effectively mitigates the blast impact, the outer container can be used repeatedly. A steel pipe was used as the main part of the both the outer container and the internal structure. To design these structures we had to predict the deformation of a steel pipe subjected to a blast load. This situation occurs when the container is used to contain a blast, because it is expected to be used only once.

Although explosion tests are useful for designing structures to contain explosive, the experiments requires a large area and are expensive when the amount of explosive is large. The information required for designing a large container should be obtained from the small−scale experiments or direct numerical simulations if the objects have a simple structure.

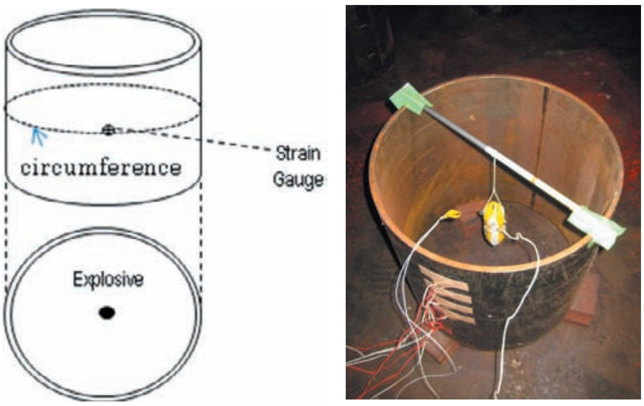
A series of internal blast loading tests for steel pipes were conducted[1]. Japanese Industrial standards were selected as samples for this experiment, because such a pipe is used as the main part of the container. The ratio of the length to the diameter is one. Composition C4 explosive was placed at the geometrical center of the pipe and was exploded using an electric detonator. The diameter of the steel pipe and the amount of explosive were varied. On the basis of our experimental results we found an empirical relation between the deformation and the pipe radius, and formulated an empirical relationship for predicting the deformation of a pipe subjected to a blast load.

The numerical simulations of these experiments were conducted using the AUTODYN code. The Johnson−Cook strength model[2] was selected. In this paper the results of numerical simulations were used for discussing the accuracy of the experimental results and the predicted values obtained by the proposed equation.

2. Experiments and numerical simulations

The diameters of the steel pipes used in the experiment were 318, 406, 508, and 660 mm. Because all pipes were Japanese Industrial standards (STK 400 JIS G3444), the ratio of the thickness to the radius of the pipe varied with the pipe size. The ratio of the diameter to the length of the steel pipe was set as one. The experimental setup is shown in Fig. 1. The dimensions of the steel pipes and the amount of composition C4 explosive are shown in Table. 1. The circumference at the midpoint of the steel pipe surface was measured before and after the experiments to observe permanent deformation. A measuring tape was used for manual circumference measurement. All measurements were carried out by more than two observers and more than two times per one shot. Difference of the circumference before and after the experiment corresponds to permanent deformation. We discuss the permanent deformation or the strain at the midpoint of the steel pipe surface, in this paper. The strain gauge measurements were also performed. The strain gauge, KFG−1−120−D16 made by KYOWA ELECTRONIC INSTRUMENTS CO, LTD., was pasted to the outer surface of the steel pipe as shown in Fig. 1. The signal conditioner and the oscilloscope were the KYOWA CDV−700 A and HIOKI 8855 Memory Hicorder, respectively.

Axisymmetric calculations were performed using the AUTODYN code. The schematic illustration of the calculation field is shown in Fig. 2. The calculation field comprised of air, steel and explosive parts. Ideal gas, Hugoniot + Mie Gruneisen, and JWL[3] equations of state (EOSs) were applied for each material. The parameters of the JWL EOS for Composition C4 are shown in Table 2. The parameters used in Johnson−Cook strength model selected for steel are shown in Table 3. The Eulerian coordinate system with about 2 mm mesh for axial and radius direction was employed for the parts of the explosive and the air, and the steel pipe was treated as the Lagrangian coordinate system which has about 1mm initial mesh size for axial and radius directions. The calculation of the fluid and structure interaction was applied. The length of the calculation field was set as 2 times of the radius of the steel pipe. The explosive was ignited from the top end using the program burn logic.



(a) Position of strain gauge (b) Steel pipe (center Comp. C4)

Fig. 1 Experimental setup for internal blast loading tests on steel pipes.

Table 1 Dimensions of the steel pipes and the range of amount of composition C4 explosive ; the thickness and diameter are the measured average values in this work.

Standard	Thickness(mm)	Diameter (mm)	Explosive (g)	Diameter of explosive (mm)
Φ318	6.706	319.2	45 − 250	35 − 48
Φ406	8.745	407.1	70 − 250	35 − 44
Φ508	9.498	508.9	125 − 300	44 − 48
Φ660	12.06	660.7	150 − 400	48

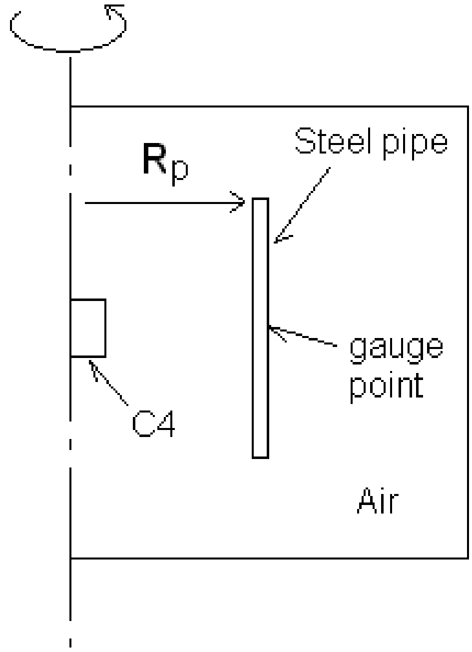


Fig. 2 Schematic illustration of the calculation field for the internal blast loading tests on steel pipes ; the calculation field is an axisymmetric, and consist of the air, steel pipe and explosive part. C4 : Composition C4 explosive, Rp ; the inner radius of steel pipe

Table 2 The JWL parameters for composition C4 explosive.

ρ_0 (g cm^{-3})	A (Mbar)	B (Mbar)	R1	R2	ω
1.4	4.7158	6.89E−02	4.587	1.1	0.37

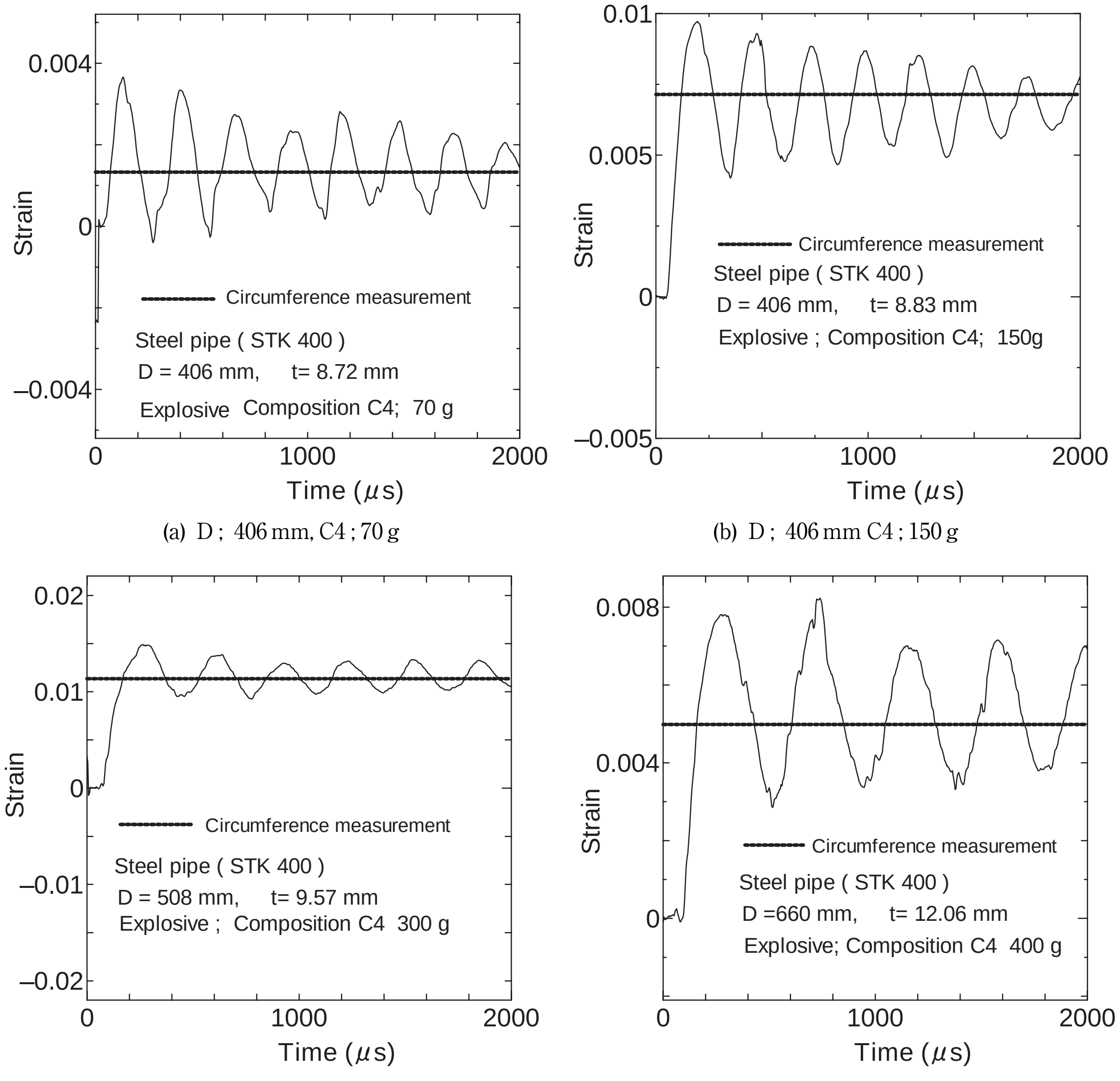
Table 3 The parameters for the Johnson and Cook strength model. $\sigma = (A + B\varepsilon^n)(1 + C \ln \varepsilon^*)(1 - T^{*m})$

Parameters	A (MPa)	B (MPa)	C	n	m
Case A	240	0	0	0.22	1
Case B	240	275	0.36	0.22	1

3. Results and discussion

3.1 Experimental results

Typical results for the strain recorded by gauge at the midpoint of the steel pipe surface are shown in Fig. 3. The measured circumferences at the midpoint of the steel pipe surface are shown in Table 4. The vertical axis in Fig. 3 corresponds to the hoop strain, which is discussed throughout this paper. The permanent strains estimated by results of circumference measurements are also shown in Fig. 3 as straight line and described in Table 4. The center of the oscillation of the strain indicates the plastic strain of the steel pipe and is in agreement with the permanent strain of the pipe estimated by the circumference



(a) D ; 406 mm, C4 ; 70 g (b) D ; 406 mm C4 ; 150 g

(c) D ; 508 mm, C4 ; 300 g (d) D ; 660 mm C4 ; 400 g

Fig. 3 The strain histories at the midpoint of the steel pipe surface by strain gauge, and the permanent strains estimated by the results of circumference measurements.

measurements. This consistency suggests that both measurements give accurate information of the amounts of both of dynamic and permanent pipe deformation. Although the dynamic strain or the deformation of the pipe can be discussed using the maximum strain recorded by the gauges, the permanent strain of the steel pipe is discussed using the results of circumference measurements.

To predict the maximum deformation of the steel pipe the scaling law was investigated. The parameters in this scaling law are the amount of explosive *W,* the pipe radius *R* and the ratio of pipe thickness to its radius *t/R*. Because the radius corresponds to the distance from the explosion center to the inner wall of the steel pipe, the distance scaled by the amount of explosive is available. The scaled distance used in this paper is the radius divided by the 1/3 rd power of the amount of explosive. The strain and the peak over pressure from the TNT explosion in free air[4] are plotted against the scaled distance in Fig. 4. It can be seen that in this region the peak pressure and strain have an approximately linear relationship with the scaled distance. In general, the amount of elastic deformation of the pipe is proportional to the static pressure through the pa-

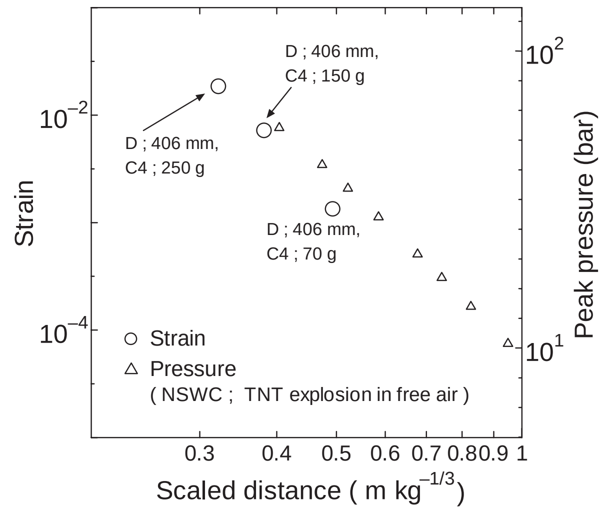


Fig. 4 The strain and the peak overpressure from the TNT explosion in free air[4] vs. the scaled distance ; the scaled distance in the case of the strain corresponds to the pipe radius divided by the 1/3 rd power of the amount of the explosive.

Table 4 The results of the circumference measurements at the midpoint of the steel pipe surface for a case of 406 mm diameter ; D and t are the diameter and thickness of the pipe ; the t/R is the ratio of thickness to radius ; the length of the circumference before and after explosion test ; the strain estimated by circumference measurements.

D(mm)	t(mm)	t/R	C4(g)	Circumference		
				Before (mm)	After (mm)	Strain
407.1	8.72	4.284E−02	70	1278.2	1279.9	1.33E−03
407.1	8.83	4.338E−02	150	1278.3	1287.5	7.20E−03
407.2	8.71	4.278E−02	200	1278.5	1294.2	1.23E−02
407.1	8.72	4.284E−02	250	1278.4	1302.4	1.88E−02

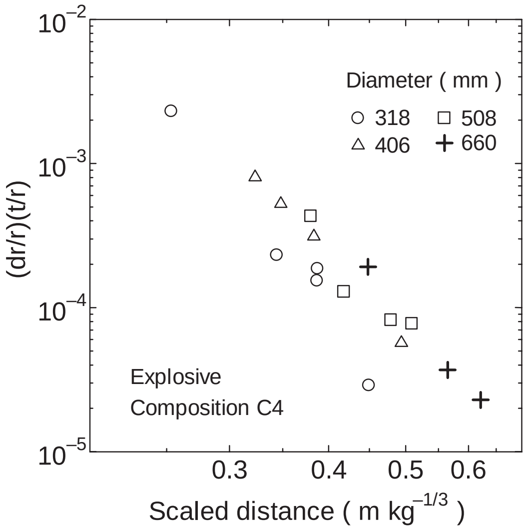


Fig. 5 The relationship between strain×t/R of the steel pipe and the scaled distance ; The scaled distance corresponds to the pipe radius divided by the 1/3 rd power of the amount of the explosive.

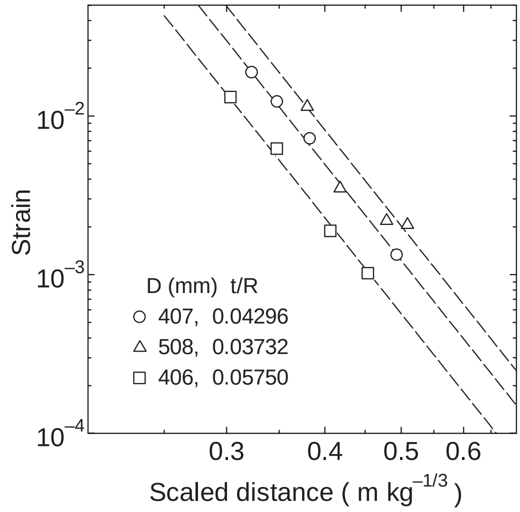


Fig. 6 The relationship between the permanent strain at the midpoint of the steel pipe surface and the scaled distance ; the scaled distance corresponds to the pipe radius divided by the 1/3 rd power of the amount of the explosive.

rameter t/R and the material strength coefficient. Although perfect plastic deformation occurs under the experimental conditions, we selected the parameter of strain ×t/R to summarize experimental data. We found an empirical relationship between the permanent deformation and the scaled distance to predict the pipe deformation as shown in Fig. 5[1]. The scaled distance and strain × t/R have an approximately linear relationship when plotted on a logarithmic scale. The scattering of the data in this figure was examined, and an empirical equation based on the scaling law was constructed to give a precise estimation of the deformation as discussed below.

3.2 Formulation of the empirical equation

The relationship between the strain and the scaled distance is shown in Fig. 6. It is convenient to select the strain as vertical the axis in the formulation. Three sizes of steel pipes were selected to formulate the empirical equation for the prediction of deformation as shown in Table 5. The data for the steel pipe of 406 mm diameter and 11.7 mm thickness were added for the formulation. From Fig. 6 it is reasonable to consider that the relationship between the strain and the scaled distance depends on t/R. The assumptions underlying the formula are that the strain and scaled distance have a linear relationship when plotted on

Table 5 The average diameters and t/R of the selected steel pipes for formulation of the empirical equation.

D (mm)	t/R	D (mm)	t/R	D (mm)	t/R
407.1	0.04296	508.9	0.03732	406.8	0.05750

a logarithmic scale, the slope of the linear relationship is unique, and the position of the linear relationship in Fig. 6 depends only on t/R. The formulation is

$$\log(\varepsilon) = a \log(S_d) + f((t/R)) \quad (1)$$

where $\varepsilon = \Delta R/R$ and S_d are the strain and scaled distance, respectively. The parameter 'a' is a constant corresponding to the slope of the dashed lines in Fig. 6 and was calculated by fitting a function to the data for a pipe with a diameter of 407 mm with t/R=0.04296.
$f(t/R)$ was obtained from each fitting line. This term is a function of t/R, and can be expressed below as.

$$f(t/R) = b \log(Kt/R) \quad (2)$$

where b and K are constants. The fitted curve for the above equation and the relationship between $f(t/R)$ and t/R are shown in Fig. 7. The final form of the proposed empirical equation is

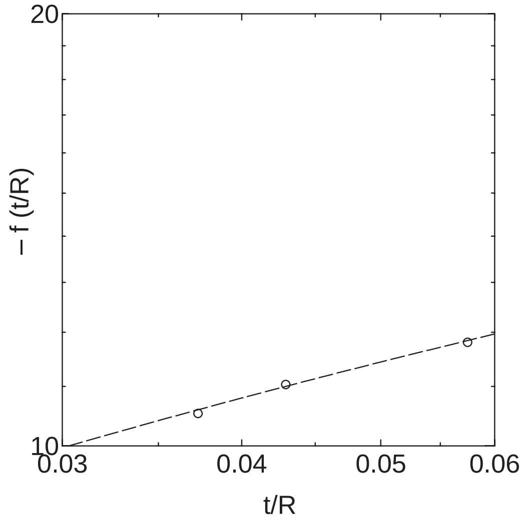


Fig. 7 The relationship between the $-f(t/R)$ and the t/R in proposed equation.

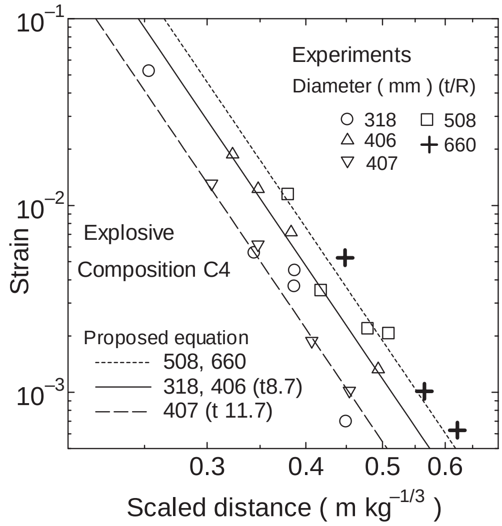


Fig. 8 The comparison of the permanent strain at the midpoint of the steel pipe surface with the experiments and the proposed equation.

Table 6 The parameters of the proposed equation for predicting the deformation of the steel pie subjected by the blast load.

a	b	K	K'
−6.2414E+00	−2.8794E+00	1.0631E+03	1.9279E−09

$$\varepsilon\,(t/R)^{-b} = K'\,(S_d)^a \tag{3}$$

The parameters obtained from our experimental results are shown in Table 6. When the size of the steel pipe and the amount of explosive are known, this equation predicts the strain, which can be easily transformed to the amount of deformation for an arbitrary amount of explosive and a pipe of arbitrary size.

3.3 Evaluation of the proposed empirical equation by comparison of experiments

To evaluate the proposed equation for predicting the amount of deformation under a blast load, the experimental results and predicted strain were compared as shown in Fig. 8. Because t/R is almost the same for pipes of 508 and 660 mm diameter, one prediction line was used. Pipes of 318 and 406 mm diameter also have similar values of t/R. With the exception of the pipe with 318 mm diameter, the prediction lines are consistent with the experimental results. In contrast, for the pipe with 318 mm diameter, all the data obtained by circumference measurements were smaller than the predicted values. This situation will be discussed on the basis of by numerical results in the next paragraph.

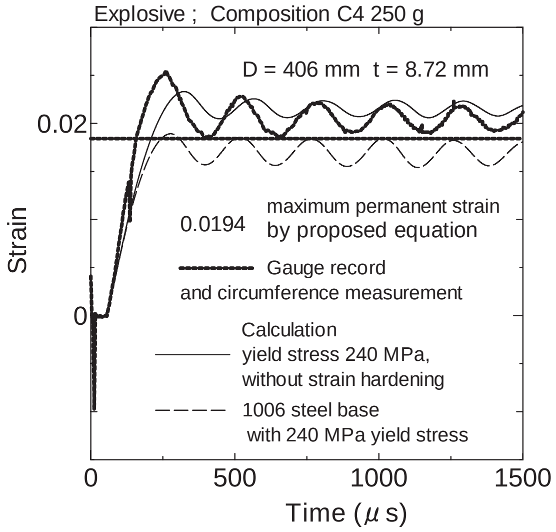
3.4 Evaluation of the proposed empirical equation by comparison with numerical results

Two different of parameter sets (case A and case B) for strength model were examined. These parameters are shown in Table 3. The yield stress was set to 240 MPa, which corresponds to the static yield stress. Strain hardening was ignored in case A, and the parameter set for 1006 steel was selected for case B. The permanent strain predicted by the proposed equation, the experiments and the simulations are compared in Fig. 9 and 10. In Fig. 9 (a) because the hardening effect was ignored in case A, the maximum strain is greater than that obtained from the experiments. On the other hand, the maximum strain estimated for case B is smaller than that in the experimental results. Fig. 9 (b) shows the same trend as Fig. 9 (a). The permanent strain predicted by our proposed formula lies between both calculation result and has almost the same value as that obtained by the circumference measurement. It can be considered that suitable parameters for the strength model of the steel pipe lies between cases A and B. In the case of the 318−mm−diameter pipe, as shown in Fig. 10, both numerical results are greater than the experimental result; however the predicted permanent strain still lies between the results of cases A and B. Upon comparison with the results in Fig. 9, this result appears reasonable.

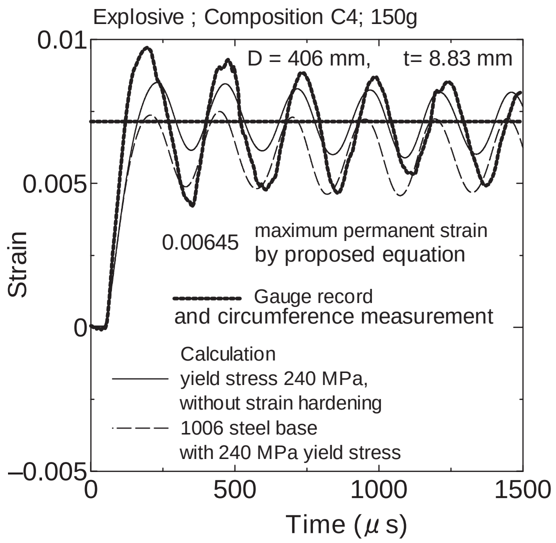
The proposed equation can predict the amount of strain, or deformation, at the midpoint of the steel pipe for an arbitrary amount of explosive and size of steel pipe. However the precise upper and lower limits for the validity of this equation are yet to be determined. The proposed empirical equation is applicable in the strain range of at least 5.0e−4 to 0.08, and a range of t/R from 0.036 to 0.058 for an arbitrary amount of explosive and for an arbitrary size of steel pipe.

4. Conclusion

A series of internal blast loading tests on steel pipes of Japanese Industrial standard have been conducted. We proposed an empirical equation for predicting the deformation of the center of such a pipe using these experimental results. The proposed empirical equation is applicable in the strain range of at least 5.0e−4 to 0.08 and a range of t/R from 0.036 to 0.058 for an arbitrary amount of explosive and for an arbitrary size of steel pipe.



(a) C4 250 g



(b) C4 150 g

Fig. 9 The comparison of the permanent strain at the midpoint of the steel pipe surface with the strain gauge records, the circumference measurements and the predicted values in the case of the 406 mm diameter.
case A ; yield stress 240 MPa without strain hardening,
case B ; 1006 steel base with 240 MPa a yield stress.

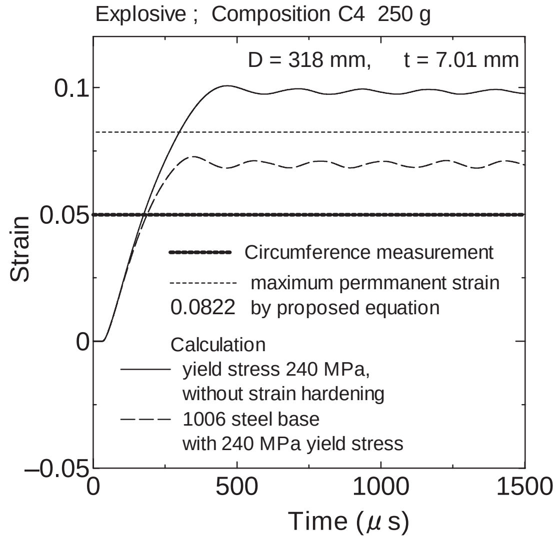


Fig.10 The comparison of the permanent strain at the midpoint of the steel pipe surface with the strain gauge records, the circumference measurements and the predicted values in the case of the 318 mm diameter.
case A ; yield stress 240 MPa without strain hardening,
case B ; 1006 steel base with 240 MPa a yield stress

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内部爆発荷重をうける鋼管の変形量予測のための経験式

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鋼管の中心に高性能爆薬を設置し爆発させる一連の試験を行った。試料は直径と長さの比が１である一般構造用鋼を使用した。実験結果をもとに，鋼管の変形量と換算距離との経験的な関係を見出した。この論文での換算距離は鋼管半径を薬量の３乗根で除したものである。実験結果をもとに変形量を予測可能な経験式を提案した。実験結果と数値計算結果により予測式の適用性を評価した。提案された予測式は，任意の薬量，任意の鋼管サイズについて変形量を予測可能である。

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