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Collapse Load and Absorbed Energy Estimation of Tubular Members Subjected to Local Lateral Loads*

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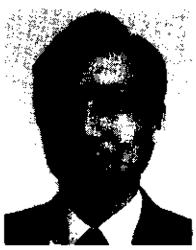

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1 Introduction

Structures consisting of steel pipes with a circular section, hereinafter simply called "steel pipe" and also called tubular structures, are being increasingly used in construction owing to their advantageous structural performance.

In particular, because of their relatively low resistance to the external flow of fluids from winds, currents, waves, etc. compared with other structural sections built up from flat plates, they have been applied to off-shore and on-shore structures, as well as to high-rise towers.[1)]

However, if a tubular structural member is subjected to a direct local lateral load, the wall can be easily deformed due to the lack of out-of-plane rigidity. This cross-sectional deformation will cause local secondary stress and reduce the overall bending stiffness. Such specific structural behaviour often dominates the ultimate strength and/or fatigue strength of tubular steel joints.

Estimation methods for the load-bearing capacity when subjected to axial force and overall bending have been already proposed by many researchers, and some of these methods have been incorporated into design specifications and rules.[2)]

However, when a local lateral load on the pipe wall such as that from a collision is involved, the absorbed energy due to plastic deformation of the steel pipe wall and also the residual strength after deformation become the dominant considerations. Several studies regarding local lateral loads have been made[3),4)] and incorporated into some design specifications.[5)]

However, many of these past studies were based on the test results from steel pipe specimens with a relatively small diameter and wall thickness, using special indentors with a sharp head such as wedges.[6)] Judging from these test conditions in the previous works, it is doubtful that the testing methods were adequate when the results are applied to large structures.

In the present study, a series of local lateral loading

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tests was conducted on large steel pipe specimens with various diameters and wall thicknesses, in order to propose a more reasonable estimation method for the ultimate strength and absorbed energy of tubular members when subjected to a collison load on their wall surface.

This report describes the loading tests, and some empirical formulas by which the collapse load and absorbed energy can be estimated are proposed. These formulas were obtained from the test results and the collapse mechanism model of the plastic deformation that occurs in steel pipes during lateral loading.

2 Test Method[7] and Test Results

Local lateral loads were applied statically to the top of the pipe specimens at the span center, which was simply supported at both ends, by a 9.8 MN (1 000 tonf) structural testing machine. The specimens were subjected to a combined concentrated lateral load and overall bending through a rigid hemispherical loading head with a tip radius of 600 mm, this being machined from a steel block and installed in the upper section of the testing machine.

Strain and deformation measurements were carried out to investigate the structural behaviour of the specimens during loading at several loading steps. The applied load was measured and monitored with a loadcell installed in the testing machine, and the reactions to the applied load were measured with two loadcells, one positioned at each end of the specimen. The strain distribution in each specimen was mesured with electrical-resistance strain gauges fitted on the surface of the pipe, and the displacement distribution was measured with electrical displacement sensors.

The applied load was recorded directly by a microcomputer, all other measurements being recorded by the microcomputor through a digital static strain meter. The system for data acquisition is shown in **Fig. 1**.

Details of the nine test specimens used are summarized in **Table 1**, including length, wall thickness and diameter of each steel pipe. The lateral load was applied repeatedly to some of the specimens to investigate the effect of load repetition on the absorbed energy and collapse load, while a monotonically increasing load was gradually applied to the other speeimens. At the initial stage of loading, the applied load was controlled by the load-control method, and deformation and strain measurements were taken at the prescribed loading steps. As soon as the specimen showed significant plastic behaviour, the control method was changed to give increasing vertical displacement of the loading head while measuring the increments of load, deformation and strain.

Tubular members subjected to a local lateral load can absorb the energy (work done) by an external force as the sum of two kinds of strain energy: (1) local denting deformation energy at the loaded point, and (2) overall bending deformation energy.

Therefore, it is useful to analyze the deformation of the specimen at the loading point by dividing it into the local denting deformation δ_d and the overall bending deformation δ_b to calculate the total absorbed energy of the specimen.

In **Figs. 2** and **3**, the typical behaviour of the two kinds of deformation are respectively illustrated. In **Table 2** are shown the local denting deformation δ_{dp}, the overall bending deformation δ_{bp} and the displacement of the loading point δ_p under the maximum load P_p.

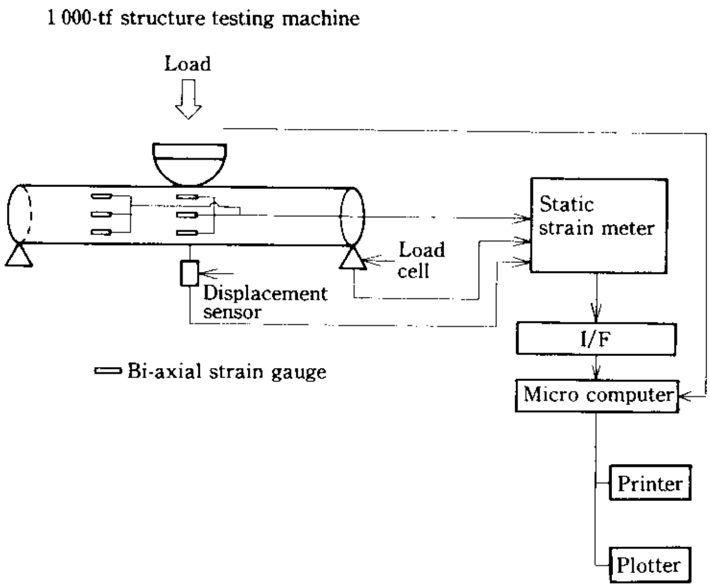

Fig. 1 Block diagram of testing system

Table 1 Dimension of test specimens and estimated values of k in Eq. (10)

Test specimen No.	Max. load P_p (tf)	Dent depth under max. load δ_{dp} (mm)	Thickness t (mm)	Mean. diameter D (mm)	Plastic section modulus of cicle Z_{pc} (mm³)	Span L (mm)	Plastic section modulus of ellipse Z_{pe} (mm³)	Eq. (10) k
					$\times 10^6$		$\times 10^6$	
1	91.6	192.9	12.98	496.02	3.194	4 000	2.205	0.35
2	63.1	171.2	12.00	496.00	2.953	5 000	2.156	0.43
3	57.9	183.5	9.44	396.86	1.487	2 500	0.923	0.19
4	50.7	167.7	9.44	396.86	1.487	3 000	0.980	0.23
5	41.3	140.2	9.44	396.86	1.487	4 000	1.075	0.30
6	75.8	157.6	11.98	394.32	1.863	3 000	1.268	0.01
7	122.9	132.4	16.01	390.39	2.441	3 000	1.796	−0.08
8	41.5	164.3	7.91	347.29	0.954	2 500	0.582	0.15
9	36.4	134.6	8.00	347.60	0.967	3 000	0.669	0.39
Mean value								0.22

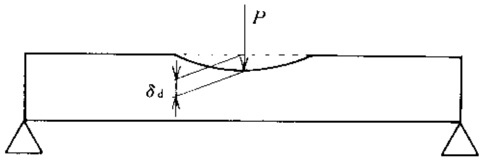

Fig. 2 Local denting deformation

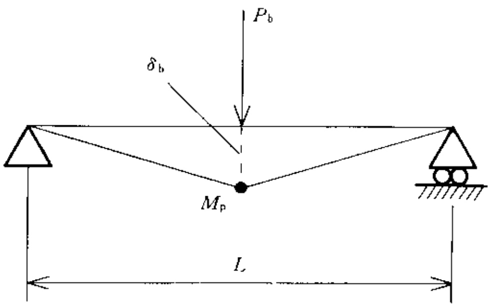

Fig. 3 Overall bending deformation

Table 2 Summary of test results

Test speci-men No.	Under the maximum load			
	Lateral load P_p (tf)	Dent depth δ_{dp} (mm)	Deflection δ_{bp} (mm)	Displacement at loading point δ_p (mm)
1	91.6	192.9	74.3	267.2
2	63.1	171.2	92.2	263.4
3	57.9	183.5	43.0	226.5
4	50.7	167.7	55.4	223.1
5	41.3	140.2	77.1	217.3
6	75.8	157.6	71.4	229.0
7	122.9	132.4	79.6	212.0
8	41.5	164.3	54.7	219.0
9	36.4	134.6	54.6	189.2

3 Discussion

3.1 Local Denting Deformation at the Loading Point

Assuming that the sectional shape of a steel pipe is perfectly circular with wall thickness t and average diameter D as shown in **Fig.** 4(a), and also assuming that the material of the steel pipe is completely elasto-plastic, the relationship between applied load P and denting deformation δ_d is given by the following equation:[6)]

$$P = \frac{1}{4} \times K\sigma_y t^2(\delta_d/D)^{1/2} \quad \cdots\cdots\cdots(1)$$

where K is a constant, σ_y is the yield stress of the steel pipe, and t and D denote the wall thickness and average diameter of the pipe, respectively.

Next, absorbed energy E_d due to denting deformation δ_d is given by Eq. (2).

$$E_d = \int_0^{\delta_d} P d(\delta_d) = \frac{1}{6} \times K\sigma_y t^2(\delta_d^3/D)^{1/2} \cdots(2)$$

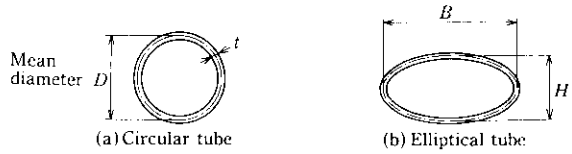

Fig. 4 Geometries

3.2 Overall Bending Deformation

Again, assuming that the material of the steel pipe is completely elasto-plastic, collapse load (ultimate load) P_b of a simply-supported pipe beam subjected to a concentrated load at its span center is given by

$$P_b = (4/L) \times M_p \quad \cdots\cdots\cdots(3)$$

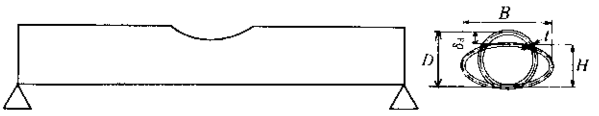

Fig. 5 Steel tube with local dent depth δ_d

where L and M_p are the span length and the fully plastic moment, respectively.

$$M_p = \sigma_y Z_p \quad \cdots\cdots(4)$$

In Eq. (4), Z_p is a plastic section modulus, and for a pipe with a circular section, it is expressed by Eq. (5).

$$Z_{pc} = D^2 t \times \left\{1 + \frac{1}{3} \times (t/D)^2\right\} \quad \cdots\cdots(5)$$

On the other hand, the steel pipe changes its sectional shape with increasing applied load, as illustrated in Fig. 4(b) due to the local denting deformation. Consequently, Z_p also becomes a function of δ_d after a certain stage has been reached. According to the test results, when the steel pipe dents locally, its sectional shape at the loading point (corresponding to the span center) changes approximately into an elliptical shape with a major and a minor axis of B and H as shown in **Fig. 5**. Plastic section modulus Z_{pe} of an elliptical pipe is expressed by

$$Z_{pe} = \frac{4}{3}\left[\left(\frac{H+t}{2}\right)^2 \times \left(\frac{B+t}{2}\right) - \left(\frac{H-t}{2}\right)^2 \times \left(\frac{B-t}{2}\right)\right]$$

$$= \frac{t}{3}(2HB + H^2 + t^2) \quad \cdots\cdots(6)$$

where

$$\left.\begin{aligned} H &= D - \delta_d \\ B &= 2D - H = D + \delta_d \end{aligned}\right\} \quad \cdots\cdots(7)$$

This relationship between B and δ_d can be obtained by assuming that the cross-sectional area of the pipe does not change even after the pipe is deformed. Substituting Eq. (7) into Eq. (6), Z_{pe} is expressed by Eq. (8).

$$Z_{pe} = D^2 \cdot t\left[1 - \frac{2}{3} \times \frac{\delta_d}{D} - \frac{1}{3} \times \left(\frac{\delta_d}{D}\right)^2 + \frac{1}{3} \times \left(\frac{t}{D}\right)^2\right]$$

$$= Z_{pc} - \frac{Dt}{3} \times \delta_d\left(2 + \frac{\delta_d}{D}\right) \quad \cdots\cdots(8)$$

In the case of no denting, by putting $\delta_d = 0$ in Eq. (8), Z_{pe} is equal to Z_{pc}. In the case of a steel pipe that has completely collapsed, by putting $\delta_d = D - t$, we can obtain the conventional relationship of $Z_{pe} = 4Dt^2/3 = Z_{pc}$, which denotes the plastic section modulus of an elliptical section with major and minor axes of $2D$ and $2t$, respectively.

Since the actual cross-section of the collapsed pipe is not exactly an elliptical shape, the actual plastic section

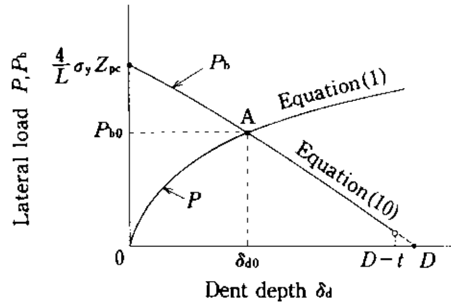

Fig. 6 Relation between lateral load and dent depth

modulus Z_p should be modified on the basis of the test results as follows:

$$Z_p = \left(1 - k \times \frac{\delta_d}{D}\right) \times Z_{pe} \quad \cdots\cdots(9)$$

where k is an empirical constant determined from the test results.

The bending collapse load of a steel pipe with denting deformation δ_d can be obtained from Eqs. (3), (4), and (9) as follows:

$$P_b = \frac{4}{L} \times \sigma_y Z_{pe}\left(1 - k \times \frac{\delta_d}{D}\right) \quad \cdots\cdots(10)$$

Load P in Eq. (1) increases with increasing δ_d as shown in **Fig. 6**. On the other hand, P_b in Eq. (10) decreases with increasing δ_d. It can be considered that a steel pipe collapses at intersection point A of the two curves, and we can obtain critical denting deformation δ_d by reading the abscissa of point A, and collapse load P_{b0} as the ordinate of point A.

Furthermore, the absorbed energy due to overall bending deformation E_b can be obtained by

$$E_b = P_{b0}\delta_b \quad \cdots\cdots(11)$$

where δ_b denotes the deformation due to overall bending.

3.3 Determination of the Empirical Constants

Typical relationships among the lateral load, denting deformation, overall bending deflection, and displacement at the loading point are shown in **Fig. 7**. The denting deformation and overall bending deflection increased simultaneously with increasing load.

For convenience shake, in the present proposed collapse model, the empirical constants to estimate the collapse load and absorbed energy can be determined by assuming that the denting deformation precedes the overall bending deflection. Thus, by equating the experimental maximum load P_p with the above-mentioned collapse load P_{b0}, and the denting deformation δ_{dp} at the maximum load with that at the collapse load δ_{d0}, point A in Fig. 6 corresponds to point A′ in Fig. 7. Consequently, K in Eq. (1) and k in Eq. (10) can be determined under the condition that both curves from Eq.

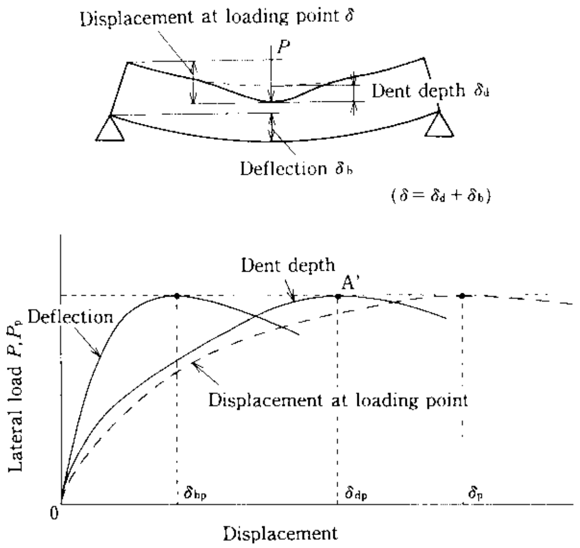

Fig. 7 Lateral load-dent depth, deflection, and displacement at loading point

Table 3 Estimated values of K in Eq. (1) and related test parameters

Test specimen No.	Max. load P_p (tf)	Dent depth under max. load δ_{dp} (mm)	Thickness t (mm)	Mean dia. D (mm)	YS σ_y (kgf/mm²)	Eq. (1) K
1	91.6	192.9	12.98	496.02	48	73
2	63.1	171.2	12.00	496.00	43	69
3	57.9	183.5	9.44	396.86	73	89
4	50.7	167.7	9.44	396.86	43	81
5	41.3	140.2	9.44	396.86	43	73
6	75.8	157.6	11.98	394.32	45	74
7	122.9	132.4	16.01	390.39	50	66
8	41.5	164.3	7.91	347.29	48	80
9	36.4	134.6	8.00	347.60	48	76
Mean value						76

(1) and Eq. (10) pass through point A'.

In **Table 3**, the values of K obtained from the test results are shown. By averaging these experimental values, we derived the following representative value for K:

$$K = 76 \quad \cdots\cdots(12)$$

Substituting this experimental constant into Eq. (1) allows Eq. (1) to be expressed as follows:

$$P = 19\sigma_y t^2(\delta_d/D)^{1/2} \quad \cdots\cdots(13)$$

Next, the value of constant k in Eq. (10) can be modified in the same way. In Table 1, the modified

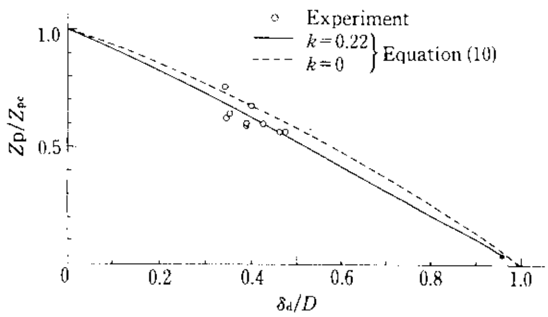

Fig. 8 Relation between Z_p and δ_d depending on k

values of k for all the specimens are listed. By averaging these experimental values for k, the mean value of k was obtained as follows:

$$k = 0.22 \quad \cdots\cdots(14)$$

In Table 1, the experimental values of k appear to show wide dispersion. However, as can be seen in **Fig. 8**, which shows the relationship between Z_p/Z_{pc} and δ_d/D, the difference between the experimental and estimated values is relatively small, as far as plastic section modulus Z_p is concerned. Consequently, Eq. (10) can be rewritten as follows:

$$P_b = \frac{4}{L} \times \sigma_y Z_{pc}\left(1 - 0.22 \times \frac{\delta_d}{D}\right) \quad \cdots\cdots(15)$$

3.4 Evaluation Method for the Collapse Load

By equating P in Eq. (13) with P_b in Eq. (15), collapse load P_{b0} and denting deformation δ_{d0} at collapse can be obtained. In **Table 4**, the estimated values are compared with the measured values. For both the col-

Table 4 Load and dent depth on collapsing

Test specimen No.	Calculation		Experiment	
	Collapse load P_{b0} (tf)	Collapse dent depth δ_{d0} (mm)	Max. load P_p (tf)	Dent depth under max. load δ_{dp} (mm)
1	96.3	194.7	91.6	192.9
2	68.8	169.8	63.1	171.2
3	52.0	202.6	57.9	183.5
4	48.7	177.9	50.7	167.7
5	43.0	138.2	41.3	140.2
6	73.7	142.3	75.8	157.6
7	123.7	100.8	122.9	132.4
8	39.5	166.7	41.5	164.3
9	37.5	143.7	36.4	134.6
Mean value	64.8 (100.3%)	159.6 (99.5%)	64.6 (100.0%)	160.5 (100.0%)

lapse load and the denting deformation at collapse, the measured values agreed well with those of estimated values to an average error of less than 1%.

3.5 Static Allowable Absorbed Energy

The static absorbed energy of a steel pipe, where "static" means a low loading speed, is given by the sum of E_d in Eq. (2) and E_b, namely, $E_d + E_b$. For practical design purposes, the critical value of δ_b should be defined when estimating the limited absorbed energy, which is called the allowable absorbed energy. Since a structure can carry an external force stably up to the maximum load, it is reasonable to define the allowable absorbed energy as the work done by the external force up to the maximum load (area S in **Fig. 9**).

According to this criterion, the critical overall bending deformation δ_b can be obtained by defining δ_b as such to give the same absorbed energy as area S in Fig. 9. Then, the magnification factor can be evaluated, which indicates to what extent over the initial yielding deflection, given in Eq. (17) by simple beam theory, the pipe member can deform stably. We can define such a magnification factor C as

$$\delta_y = \frac{L^2\sigma_y}{6E(D+t)} \quad \cdots\cdots(16)$$

$$\delta_b = C\delta_y \quad \cdots\cdots(17)$$

In **Table 5**, the experimental values of C obtained by the test procedure are also listed, so that the average of the experimental values of C can be obtained.

$$C = 9.3 \quad \cdots\cdots(18)$$

Finally, the empirical formula for the static allowable absorbed energy can be expressed in a general form as follows:

$$E = \frac{1}{6} \times K\sigma_y t^2\left(\frac{\delta_{d0}^{\,3}}{D}\right)^{1/2} + P_{b0}C\delta_y \quad \cdots\cdots(19)$$

In **Fig. 10**, Eq. (19) is illustrated in curve form in relation to lateral load P and displacement δ at the loading point. In **Table 6**, the absorbed energy estimated by Eq.

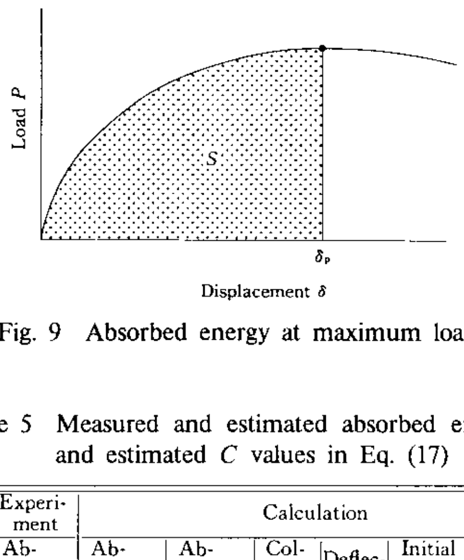

Fig. 9 Absorbed energy at maximum load

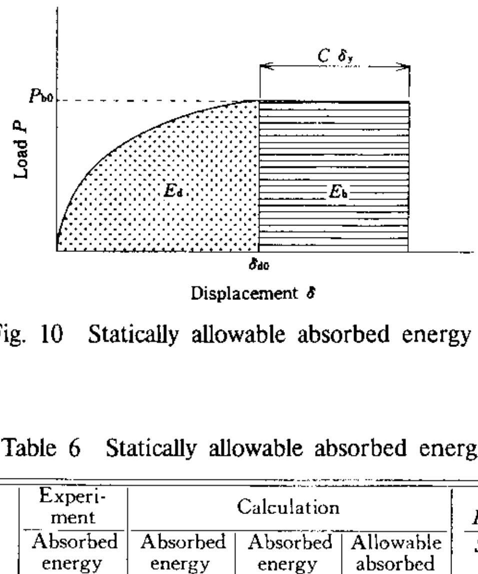

Fig. 10 Statically allowable absorbed energy E

Table 5 Measured and estimated absorbed energy and estimated C values in Eq. (17)

Test specimen No.	Experiment: Absorbed energy S (tf·cm)	Calculation: Absorbed energy E_d (tf·cm)	Absorbed energy E_b (tf·cm)	Collapse load P_{b0} (tf)	Deflection δ_b (mm)	Initial yielding deflection δ_y (mm)	Eq. (17) C
1	1 979	1 250	729	96.3	75.7	12.27	6.2
2	1 358	779	579	68.8	84.1	17.20	(4.9)
3	1 013	703	310	52.0	59.7	5.06	11.8
4	902	578	324	48.7	66.5	7.28	9.1
5	732	396	336	43.0	78.1	12.95	6.0
6	1 418	699	719	73.7	97.5	7.73	12.6
7	2 152	831	1 321	123.7	106.8	8.87	12.0
8	726	439	287	39.5	72.5	6.61	11.0
9	550	360	190	37.5	50.8	9.51	5.4
Mean value							9.3 (8.8)*

* When included No. 2 data.

Table 6 Statically allowable absorbed energy

Test specimen No.	Experiment: Absorbed energy S (tf·cm)	Calculation: Absorbed energy E_d (tf·cm)	Absorbed energy E_b (tf·cm)	Allowable absorbed energy E(tf·cm)	$\frac{E}{S} \times 100$ (%)
1	1 979	1 250	1 094	2 344	118.4
2	1 358	779	(1039)	(1818)	133.9
3	1 013	703	244	946	93.4
4	902	578	329	907	100.6
5	732	396	516	911	124.5
6	1 418	699	528	1 227	86.5
7	2 152	831	1 017	1 848	85.9
8	726	439	242	681	93.8
9	550	360	330	690	125.5
Mean value					103.6 (106.9)*

* When included No. 2 data

(19) is compared with that from the loading test.

The table shows that the estimated values agree well with the experimental values to an average error of 5%, which will be sufficient for practical design purposes.

4 Conclusions

A method for estimating the collapse load and absorbed energy of a tubular member that is subjected to a local lateral load on its wall surface has been proposed to predict the structural behaviour of large tubular members subjected to collision loading.

A series of concentrated lateral loading tests were conducted on large steel pipe specimens with several diameters and wall thicknesses. On the basis of the test results, the collapse mechanism for a steel pipe was modeled in a simple form, and semi-empirical formulas to estimate the collapse load and absorbed energy were derived.

(1) Collapse Load P_{d0} and Denting Deformation δ_{d0} at Collapse:

By equating reaction force P due to local denting with P_b due to overall bending, denting deformation at collapse, δ_{d0}, was obtained, and collapse load P_{d0} was obtained as the load which corresponds to that critical deformation.

(2) Static Allowable Absorbed Energy (E):

$$E = \frac{1}{6} K \sigma_y t^2 \left(\frac{\delta_{d0}{}^3}{D} \right)^{1/2} + P_{b0} C \delta_y$$

where $K = 76$, $C = 9.3$

In derivating these formulas, some simplifications have been made in the relationship between the lateral load and denting deformation, and in neglecting the loss in sectional rigidity due to local out-of-plane deformation.

Despite these simplifications, the proposed estimation method well explained the test results.

The semi-empirical formulas obtained here may more applicable than others for the design of large tubular structures that are subjected to lateral loads, because they were obtained from test results of large steel pipe specimens.

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