Technical Paper

大 韓 造 船 學 會 誌
第26卷 第4號 1989年 12月
Journal of the Society of Naval Architect of Korea
Vol. 26, No. 4, December 1989

Damage Estimation for Offshore Tubular Members Under Quasi-Static Loading

by

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準靜的荷重을 받는 海洋構造物의 圓筒部材에 대한 損傷豫測

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Abstract

The present study attempts to develop the theoretical model for the damage estimation of offshore tubular members which are subjected to the accidental impact loads due to collision, falling objects and so on. For the reasons of the simplicity of the problem being considered, however, this paper postulates that the accidental load can be approximated to be the quasi-static one, in which dynamic effects are negelcted. Based upon the theoretical and experimental results which are obtained from the present study as well as the existing literature, the load-displacement relations taking the interaction effect between the local denting and the global bending deformation into account are presented in the explicit form when the concentrated lateral load acts on the tubular member whose end condition is supposed to be rotationally free and axially restrained, in which membrane forces develop. Thus, the practical estimation of damage deformation for the local denting and the global bending damage of tubular members against the accidental loads is possible and also the collision absorption capability of the member can be calculated by performing the integration of the area below the given load-displacement curves, provided that all the energy is dissipated to the deforming the member itself.

要 約

本 論文에서는 衝突이나 重量物 落下등에 의한 事故荷重을 받는 海洋構造物의 圓筒部材에 대한 損傷變形擧動을 實用的으로 推定할 수 있는 새로운 損傷豫測 모델을 提案한다. 本 論文은 荷重速度가 比較的 느리고 準靜的 問題로서 다룰수 있는 경우만을 對象으로 하고 있다. 本硏究에서 취급하는 圓筒部材는 兩端單純 支持되어 있고 軸方向의 變位는 拘束되어 있으며, 荷重은 部材의 中央位置에서 橫方向으로 作用한다고 假定한다.

지금까지의 硏究成果 및 本 硏究에서 直接 遂行한 實驗結果를 바탕으로 事故荷重作用時의 圓筒部

• 본 논문은 1989년도 대한조선학회 춘계연구발표회에서 발표된 논문임.
• Manuscript received : May 30, 1989, Revised manuscript received : August 3, 1989
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材에 대한 損傷變形擧動을 詳細히 把握하고, 局部 Dent 損傷 및 全體的인 굽힘 처짐의 相關效果를 考慮한 荷重—損傷變形 關係式을 導出하였으며, 實際的인 圓筒部材에 대한 實驗結果와 本硏究에서 提案한 豫測 모델에 의한 推定結果는 잘 對應하고 있다는 것을 確認하였다. 特히, 이 같은 荷重狀態下에서의 實際部材의 損傷變形擧動에 대하여는 局部 Dent 損傷과 全體的인 굽힘처짐의 相關效果가 매우 크다는 것을 알았으며, 本豫測 모델은 이들의 效果도 잘 나타내고 있다.

1. Introduction

With the strengthening of code requirements for the structural integrity, the safety assessment of offshore platforms against the accidental impact loads due to collision, falling objects and so on becomes of great interest.

For the purpose of evaluating the safety of offshore platforms against the accidental loads, the workscope may become three-fold [1,2]: First is to clarify the deformation characteristics of single members under the accidental loads. This part is provided for the information of the amount of damage which will be used as input data to perform further workscope described in the subsequent and also makes possible to estimate the collision energy absorption capability of the member which is obtained by the integrating the area below the load-displacement curve. Second is to evaluate the residual strength of the damaged members under actual live loads. For this part, the influence of the magnitude and the location of damage, etc. on the load-carrying capacity of the member will be investigated. And finally analysis of progressive collapse behaviour for overall structures having the damaged members should be performed so that the integrity of offshore platforms against the accidental loads can be checked through integrating the area below the load-deformation curve for the whole structure. In order to carry out this task, an efficient numerical method for large size structures as offshore platforms should be developed in advance.

The present study is concerned with the first task described above where the theoretical model is developed for the damage estimation of single members which are subjected to the accidental impact loads from collision, dropped objects and so on. Here, emphasis of the paper is placed on the formulation of the load-displacement curves representing damage deformation characteristics in addition to the evaluation of the energy absorption capability because it is essential to know the amount of damage in performing further workscopes. Unstiffened tubular members are selected for the objective since they are typical components in general offshore platforms. Also, since in general the structural response under impact loads which make a dynamical phenomenon is difficult to treat, this paper postulates that the accidental loads can be approximated to quasi-static ones, so that dynamic effects are neglected. The end condition of the member is supposed to be rotationally free and axially restrained so that the membrane action in the longitudinal direction develops.

When a tubular member of offshore platforms is subjected to the accidental loads, damage deformation characteristics may be split into the following two main modes, depending upon the intensity of the impact, the geometry and material properties of the member, end condition and so on [1,2]:

1) Local denting damage without the global bending deformation, which forms at the point of applied loads (Fig. 1.a).
2) Global bending damage without the local denting damage, which may be identified with the initial deflection of the member (Fig. 1.b).

In reality, however, a combined mode of two main modes described above is appeared (Fig. 1.c) and as the load increases further proceeding of each damage deformation continues. Thus, the interaction effect between the local denting and the global bending deformation should be included for the actual damage estimation. Also, since it is impractical to depend upon the experiments only, theoretical model is necessary for the damage estimation of the member.

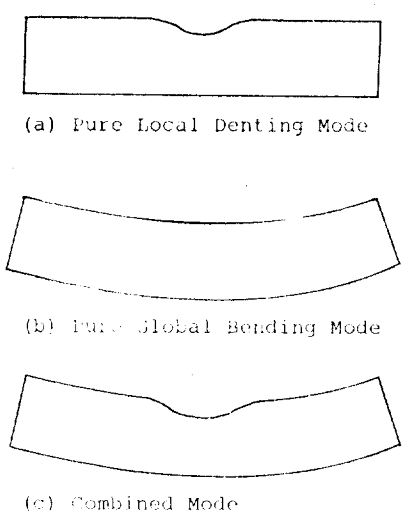

Fig. 1 Damage deformation mode of tubes under accidental loads

In the present paper, the load-dent depth relation for pure local denting damage mode and the load-global bending deflection relation for pure global bending damage mode are first derived based on the existing research data and then using the experimental results conducted in the present study, the interaction effect between the local denting and the global bending deformation is approximately incorporated in each explicit load-displacement relation.

2. Previous Models

As mentioned in the preceeding section, actual tubular members against the accidental loads undergo a combined mode of the local denting and the global bending deformation. However, since the transition between these two main modes is difficult to define, they have been treated separately in the previous works. Here, the literature related to the theoretical models for the damage estimation of tubular members against accidental loads which can be approximated to the quasi-static ones is briefly surveyed.

de Runtz and Hodge (1963)[3] proposed so called a ring model for the crushing of a tube under the compressing two opposed flat plates, which can be applied to the local denting damage estimation. In this model the load is applied by two opposed and parallel flat rigid plates in contact with the unit length ring. They derived the load-dent depth relation in very simple explicit form in the post-yielding range of the ring, using the rigid perfectly plastic theory, in which no strain hardening effect is taken into account.

Watson, Reid, Johnson and Thomas (1976)[4] developed so called an indention model for the crushing of a tube under the action of two opposed wedged-shaped indentors. This method may give more accurate results for the energy absorption capability rather than the ring model but the calculation procedure seems to be somewhat complicated and also no explicit deformation history is avaliable.

Reid and Reddy (1978)[5] advanced the ring model [3] so as to include the effect of the strain hardening. They produced a procedure for the local denting damage estimation but this procedure is also somewhat complex.

de Oliveira (1979)[6] developed a model for the estimation of pure local denting damage. In this model the shape of the local denting is approximated to the wedge-shaped collapse mechanism and then applying the rigid perfectly plastic theory in which characteristic dimensions of the wedge can vary, total energy dissipation is calculated but the explicit loaddisplacement relation is not produced.

Furnes and Amdahl (1980)[7] suggested a similar model with de Oliveira[6] but in this model the characteristic dimensions of the wedge can not vary and then the load-displacement relation is produced.

Søreide (1981)[8] described a simple model for pure global bending deformation of axially restrained tubular members under the lateral load considering the plastic hinge mechanism for the member, in which the effect of membrane forces is taken into account. And using the rigid perfectly plastic theory, the load-global bending deflection relation after the formation of the mechanism is derived.

de Oliveira (1981)[9] also produced the load-global bending deflection relation of axially restrained tubular members which are subjected to the lateral load at any position of the beam. The effect of membrane forces is taken into consideration by using the concept of the reduced moment at the plastic hinge.

Soares and Søreide (1983)[10] extended Søreide's model[8] for pure global bending deformation of tubular members under the lateral load. In addition to the interaction effect between the lateral load and the axial load, they discussed the influence of various end conditions and different load distributions.

Ellinas and Walker (1983)[11] described the load-displacement relations for the local denting as well as the global bending deformation. For local denting damage estimation, they used the result derived by Watson et al.[4] and then modified it by multiplying a correction factor based on the experimental results. Also, for global bending damage estimation of the tubular member whose end condition is supposed to be rotationally restrained and axially free, they produced the lode-global bending deflection relation which contains the reduction effect of the bending stiffness due to local denting damage by using the concept of the reduced plastic moment.

Richards and Andronicou (1985)[12] also suggested the simple model for the damage estimation of tubular members against accidental loads. In this method the estimation formula of the local denting damage has nearly same form with that by Ellinas et al.[11] but this model assumes that the shape of the original circular cross-section in the dent region does not change. Instead, material properties such as yielding strength and stiffness are considered to be reduced, in which the degree of the reduction is determined based on the empirical formula. Also, for the global bending damage mode of axially restrained tubular members in which membrane forces that affect to the local denting deformation develop, they presented a calculation procedure of the energy absorption capability of the member taking the interaction effect between the local denting and the global bending deformation due to the presence of the membrane forces into consideration but the load-displacement relation is not available.

Wierzbicki and Suh (1986)[13] suggested so called a combined ring and shell model for pure local denting damage estimation of tubular members. The philosophy of this model is based that a tube consists of a series of unconnected rings with unit length and a bundle of unconnected generators. Then, applying the principle of virtual work for the tube with rigid plastic material they derived the load-dent depth relation for the member with various end conditions.

As a result of the literature survey described above, it is concluded that any theoretical model producing the load-displacement relation which contains the interation effect between the local denting and the global bending damage has been rarely seen.

3. Proposed Model for Pure Damage Mode

In order to derive the load-displacement relations for the local denting damage mode as wells as the global bending damage mode, taking the interaction effect between two damage modes into account, deformation characteristics for each damage mode in which pure local denting and pure global bending are concerned separately is first investigated based on the existing research data and then the interaction effect between two main damage modes is approximately incorporated in each load-displacement relation which is described in section 5.

3.1. Pure Local Denting Damage

A tubular member with finite length on a rigid foundation, subjected to a concentrated lateral load, P, as shown in Fig. 2 is considered.

The tube can be moved freely in the longitudinal direction but is restrained to the rotation.

In this case, as the load increases pure local denting damage at the tube wall without the global bending deformation will occur, although the ovality of the cross-section at the position of the applied load may also take place.

Wierzbicki and Suh[13] produced the lateral load-dent depth relation for this problem, applying the

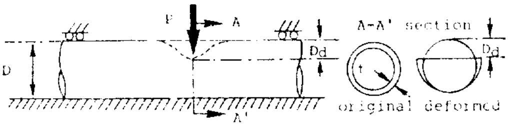

Fig. 2 Configuration of the pure local denting damage of a tube on the rigid foundation

principle of virtual work, in which no strain hardening effect is taken into account since rigid plastic material is assumed.

The form of the load-dent depth relation derived by Wierzbicki et al.[13] reads

$$P/(M_0\sqrt{D/t})=16K_N\sqrt{\pi/1.5D_d/D} \quad (1)$$

where, D : the diameter of the tube
t : the wall thickness
M_0 : the fully plastic bending moment in the circumferential of the unit length ring $(=\sigma_0 t^2/4)$
K_N : the correction factor which is expressed in terms of the axial force, depending on by the axially restrained end condition

In the case of the end condition under consideration, which is axially free and rotationally restrained, K_N of Eq. (1) is given as[13]

$$K_N=\sqrt{3/4} \quad (2)$$

3.2. Pure Global Bending Damage

As shown in Fig. 3.a, a rotationally free and axially restrained tubular member subjected to a concentrated lateral load at the midspan is considered.

In order to derive the load-pure global bending deflection relation of the member, it is assumed that no local denting and no local buckling take place at tube wall.

Then, the present method decomposes into two parts: One is the part of the elastic small deflection analysis in the pre-yielding range and another is the rigid perfectly plastic analysis for the plastic hinge mechanism of the member, after the applied load, P reaches the collapse load.

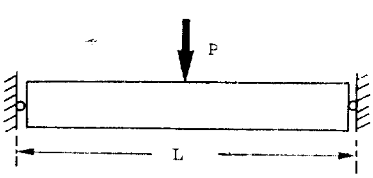

Fig. 3.a Loading and end condition of the tube

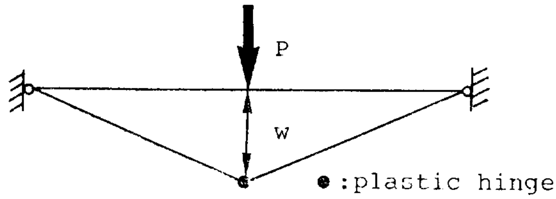

Fig. 3.b Plastic hinge mechanism of the tube under lateral load

In the case of the elastic small deflection range, the load, P-deflection, w easily reads

$$P=48EI/L^3 w \quad (3)$$

where, L : the length of the member
E : Young's modulus
I : the moment of inertia for the cross-section of the member $(=\pi R^3 t)$

It is considered that when a plastic hinge is formed at the position of the applied load collapse mechanism of the member will be emerged. Since the axial movement at ends is restrained, axial forces develop as the deflection increases. As far as the small deflection is concerned, however, the membrane effect may be neglected. Thus, the plastic hinge mechanism, as shown in Fig. 3.b is supposed to be appeared when the bending moment, M at the position of the applied load reaches the fully plastic capacity, M_p under pure bending moment. As a result, Eq. (3) is available in the range of $M<M_p$, in which $M=PL/4$, $M_p=\sigma_0 D^2 t$.

At the large deflection range, however, the membrane effect may increase further and is not negligible. In this case the bending moment at the plastic hinge will move at the interaction surface of the axial force and the bending moment, which is defined for the fully plastic stress distribution at the hinge.

The interaction relation between the bending moment, M and the axial force, N at the plastic hinge of the position of the applied load is expressed, for the undamaged member as[8]

$$M/M_p-\cos(\pi N/2N_p)=0 \quad (4)$$

where, M_p : the fully plastic capacity under pure bending moment, which for the undamaged member is calculated by $M_p=\sigma_0 D^2 t$

N_p : the fully plastic capacity under pure axial force, which for the undamaged member is calculated by $N_p=\sigma_0 \pi D t$

For three hinge mechanism of the member as indicated in Fig. 3.b, the load, P-deflection, w relation reads[10]

$$P/P_0=\sqrt{1-(2w/D)^2}+(2w/D)\sin^{-1}(2w/D) \quad ; \ 2w/D\leq 1 \qquad (5.a)$$

$$P/P_0=\pi w/D \quad ; \ 2w/D>1 \qquad (5.b)$$

where, P_0 : the plastic collapse load of a tubular member under lateral load at center for which end condition is axially free $(=4M_p/L=4\sigma_0 D^2 t/L)$.

Thus, Eq. (5) is available in the range of $M\geq M_p$ (or $P\geq P_0$).

4. Experimental Study

In order to investigate the actual deformation characteristics of the local denting and the global bending damage, the experimental study using small scale specimen of mild steel material is carried out.

Dimensions of tube specimen tested here are in the range of $23<D/t<60$ and $9<L/D<30$, which is identified with those of actual offshore platforms.

Initial bending deflection of the tubes was carefully inspected but its maximum magnitude was about $w_0/L=0.0004$. Thus, any influence of the initial bending deflection on the deformation characteristics of specimen may not be expected. However, since no stress release for the tubes was made, some residual stresses might be existed.

For getting material properties of the tubes such as yielding stress, σ_0 and Young's modulus, E uniaxial tension test was performed for two specimen of each series of the tubes. Then, mean values obtained from the test, which are listed in Table 1 are applied to the present calculation.

4.1. Pure Local Denting Damage Test

Deformation characteristics for pure local denting damage of tubular members under the concentrated lateral load which is applied by the actuator with the rigid indentor is investigated, varying the shape and size of the indentor.

Test setup is shown in Fig. 4 and Photo 1. Tubes are on the rigid foundation of 400mm length, which has roundness at the contact surface in opposed side of the tube. In order to protect the occurrence of the bending beam deformation (so that pure local denting deformation mode is recalled), roller support which permits the axial movement but restrains the deformation of the loading direction is arranged at the close of tube ends. As a pre-test, although the effect of the location of the roller support on the deformation characteristics was observed, no discrepancy was found (for PD1 specimen).

Then, 15 specimen whose dimensions are listed in Table 1 were tested, in which the loading speed was about 0.05mm/sec.

Fig. 5 shows the load-dent depth relation of the tubes, varying D/t ratio and the shape and size of the indentor. It is clear from Fig. 5 that if the lateral load reaches a critical value, the stiffness for the local denting deformation is seriously reduced, in which the critical load increases with the decre-

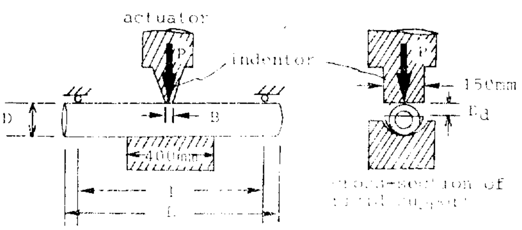

Fig. 4 Test setup for pure local denting mode

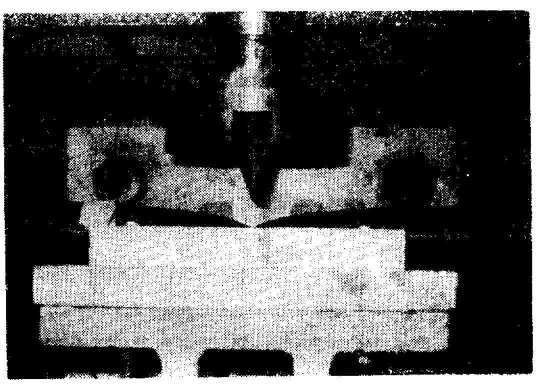

Photo 1 Test setup for pure local denting mode

Table 1 Specimen description of pure local denting damage test (PD series)

Specimen ID	Outer dia. D(mm)	Wall thick t(mm)	Length L(mm)	Indentor breadth B(mm)	Yield stresss σ_0 (kg/mm²)	Length bet'n support l(mm)	D/t	L/D	Ultimate stress σ_u(kg/mm²)
PD1	75.55	2.15	2,110	5	30.25	2,292	35.14	27.93	37.19
PD2	75.70	2.20	2,110	5	30.25	1,400	34.41	27.87	30.19
PD3	75.55	2.15	1,500	5	30.25	1,400	35.14	19.85	30.19
PD4	75.55	2.15	2,110	5	30.25	1,800	35.14	27.93	30.19
PD5	76.15	3.15	1,500	5	29.16	1,400	24.17	19.70	35.80
PD6	75.60	2.20	1,500	5	30.25	1,400	34.36	19.84	37.19
PD7	76.10	1.30	1,500	5	30.10	1,400	58.54	19.71	37.56
PD8	75.63	3.25	1,500	50	29.16	1,400	23.27	19.83	35.80
PD9	75.55	2.20	1,500	50	30.25	1,400	34.34	19.85	37.19
PD10	76.10	1.40	1,500	50	30.16	1,400	54.36	19.71	37.56
PD11	76.20	3.25	1,500	100	29.16	1,400	23.45	19.69	35.80
PD12	75.65	2.25	1,500	100	30.25	1,400	33.62	19.83	37.19
PD13	76.60	1.35	1,500	100	30.16	1,400	56.74	19.58	37.56
PD14	76.20	3.15	1,500	150	29.16	1,400	24.19	19.69	35.80
PD15	75.75	2.35	1,500	150	30.25	1,400	32.23	19.80	37.19
PD16	76.10	1.35	1,500	150	30.16	1,400	56.37	19.71	37.56

note : E=22,400kg/mm² : mean Young's modulus
σ_0 : Yield stress at 0.2% strain

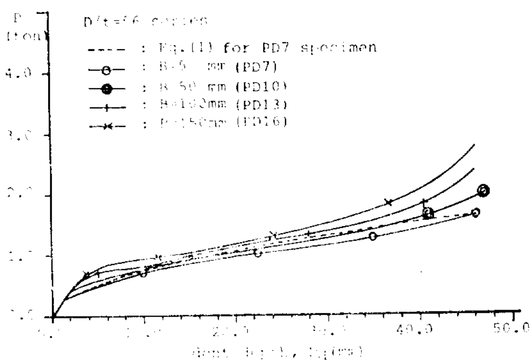

Fig. 5.a The load-dent depth relation

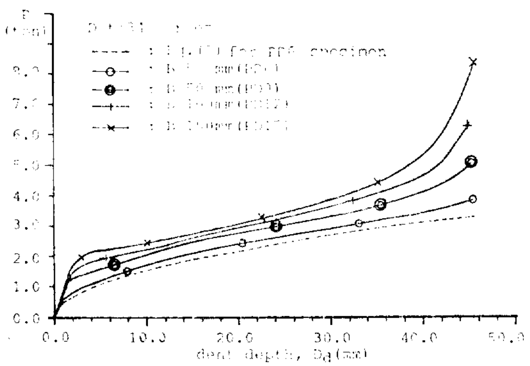

Fig. 5.b The load-dent depth relation

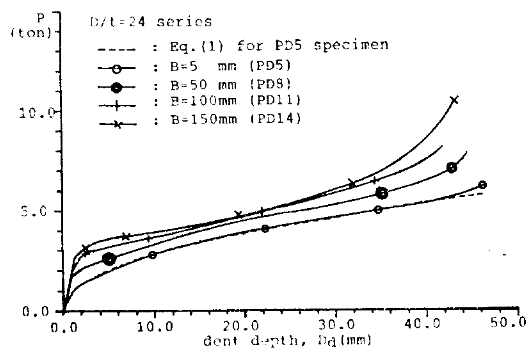

Fig. 5.c The load-dent depth relation

asing of D/t ratio. Also, when the indentor approached nearly to the rigid foundation, the resistance at the opposed side of the loading point is very large so that the increasing rate of the dent depth is rapidly reduced. And with the increasing of the breadth of the indentor, B, the critical load of the tube tends to be increased but its effect may be negligible. In the same figures, the results calculated by Eq. (1), in which Eq. (2) is used for K_N are also compared and it is obvious that the accuracy of Eq. (1) is sufficient for the practical purpose.

4.2. Global Beam Test

In order to clarify the interaction effect between the local denting and the global bending deformation of the tube, global beam test is conducted. The end condition is set to be rotationally free and axially restrained. The lateral load is applied by the knife-shaped indentor, whose breadth is 5mm. Fig. 6 and Photo 2 represents the test setup. The tube end is carefully set so as to eliminate any axial forces in the beginning, in which the degree of the action of axial forces due to bolt screwing for setting of the tube end is checked by strain gauge attached at the close to the tube end.

Then, 9 specimen whose dimensions and material properties are listed in Table 2 are tested, in which the loading speed is also about 0.05mm/sec. Lateral displacement at two points which are the loading point (upper point) and the opposed side (lower point) are measured by LVDT.

Table 2 Specimen description of global beam test (BD series)

Specimen ID	Outer dia. D(mm)	Wall thick t(mm)	Length L(mm)	Yield stress σ_0(kg/mm²)	D/t	L/D	Ultimate stress σ_u(kg/mm²)
BD1	76.50	3.25	692	29.16	23.54	9.05	35.80
BD2	75.50	2.20	692	30.25	34.32	9.17	37.19
BD3	76.05	1.25	692	30.10	60.84	9.10	37.56
BD4	76.50	3.30	1,292	29.16	23.18	16.89	35.80
BD5	75.50	2.20	1,292	30.25	34.32	17.11	37.19
BD6	76.20	1.35	1,292	30.10	56.44	16.96	37.56
BD7	75.60	3.30	2,292	29.16	23.18	29.96	35.80
BD8	75.55	2.20	2,292	30.25	34.34	30.34	37.19
BD9	76.20	1.25	2,292	30.10	60.96	30.08	37.56

note : E=22,400kg/mm² : mean Young's modulus
σ_0 : Yield stress at 0.2% strain

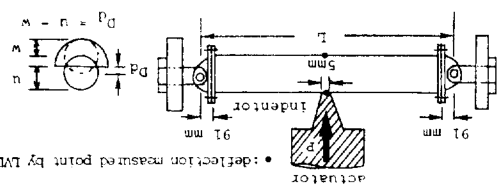

Fig. 6 Test setup for global beam deformation as well as local denting damage

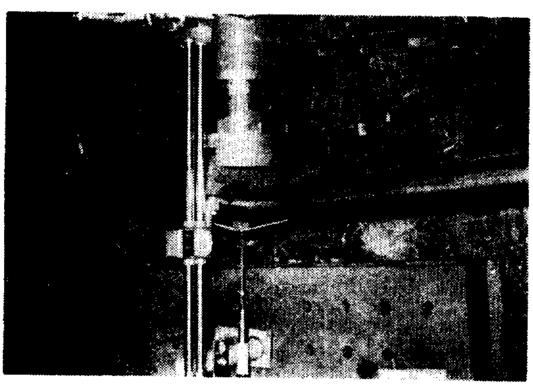

Photo 2 Test setup for global beam deformation as well as local denting damage

For the prediction of the damage at the upper bound, the lateral displacement measured and the

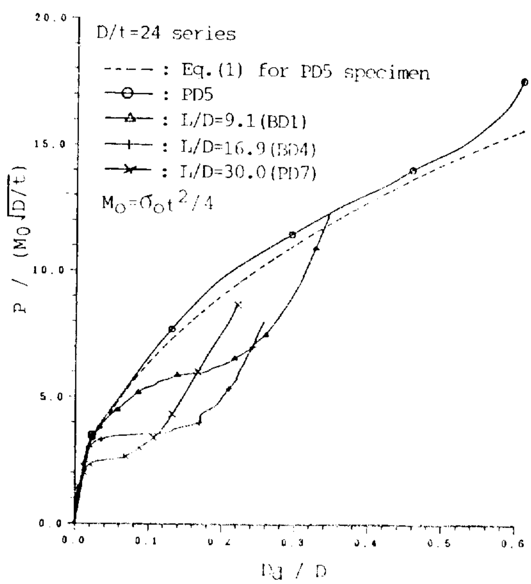

Fig. 7.a The load-dent depth relation

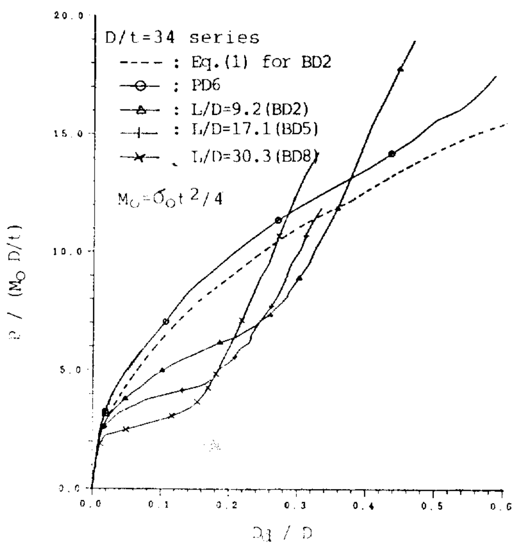

Fig. 7.b The load-dent depth relation

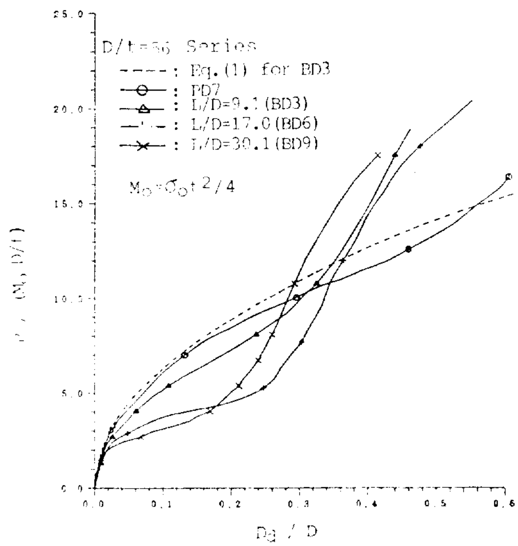

Fig. 7.c The load-dent depth relation

discrepancy between two displacements measured at upper and lower point is supposed to be the local denting deformation.

The load-displacement relations are indicated in Fig. 7 for the local denting deformation and in Fig. 8 for the global bndineg deformation.

It is clear from Fig. 7 and 8 that deformation characteristics taking the interaction effect between the local denting and the global bending damage into account is very complicated and quite different comparing with those of pure damage modes.

For the local denting behaviour, shown in Fig. 7, it is observed that the critical load is decreased with the increasing of L/D ratio because the bending moment at the loading point becomes to be larger, and after the plastic hinge mechanism is formed, the increasing rate of the dent depth is rapidly decreased since the action of the axial forces is dominant in this range.

On the other hand, for the global bending beha-

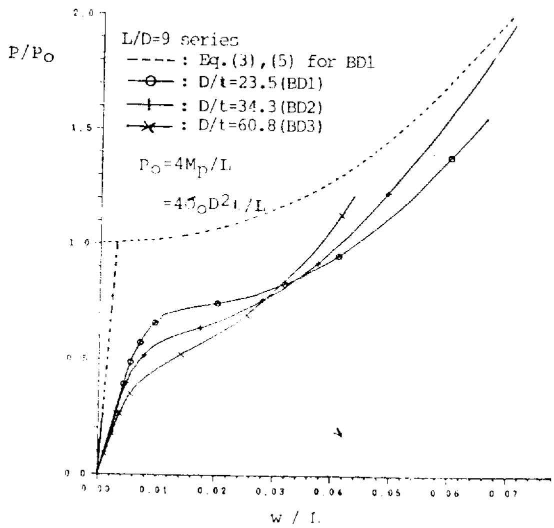

Fig. 8.a The load-deflection relation

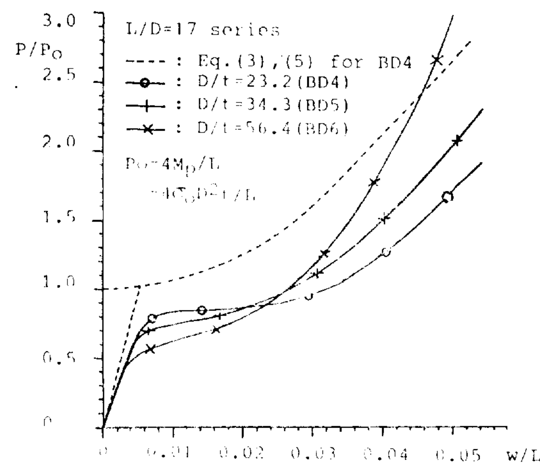

Fig. 8.b The load-deflection curve

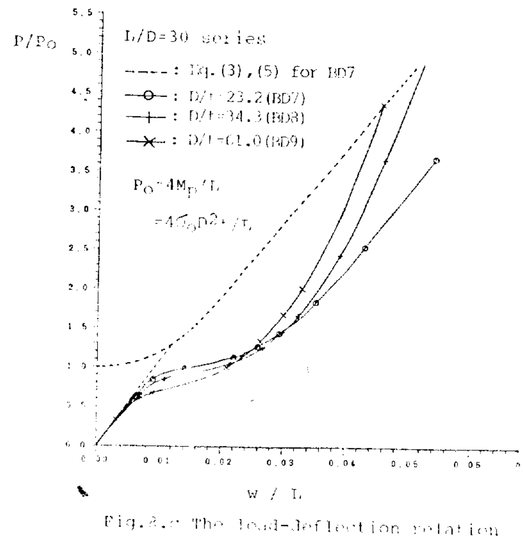

Fig. 8. c The load-deflection relation

viour as indicated in Fig. 8, the magnitude of the fully plastic bending moment at the cross-section in the local dent region is reduced so that the plastic hinge mechanism is appeared in lower lateral load.

5. Proposed Model Considering Interaction Effect Between Local Denting and Global Bending Damage

As observed through the experimental results indicated in sec. 4, the interaction effect between the local denting and global bending on deformation behaviour of the axially restrained tubular member subjected to the lateral load is significant.

Damage deformation characteristics including the interaction effect between two main damage modes is summarized as

1) For the local denting damage:

—when the magnitude of the local dent is small, the deformation characteristics is supposed to be same with the case of the pure local denting damage mode

—the critical load is reduced because of the action of the bending moent

—the axial forces which are arise from the axially restrained end condition and also become larger as the bending deflection increases resist to the increasing of local denting deformation

2) For the global bending damage:

—when the magnitude of the lateral load is small, the deformation characteristics is supposed to be same with the case of the pure global bending mode

—the fully plastic bending capacity at the cross-section in the local dent region is reduced so that the plastic hinge mechanism of the member is appeared at the lower load

—the axial forces also resist to the increasing of the global bending deformation

5.1. Practical Formula for Damage Estimation

Based on the experimental results conducted here, the following load-displacement relation for damage estimation taking the interaction effect between the local denting and the global bending mode into account may be gained.

1) At the small displacement range before the plastic hinge mechanism of the member is formed:

Local Denting Damage

In this range, local denting damage can be estimated by Eq. (1), which is an expression for pure local denting deformation since the magnitude of the bending deflection is considered to be small.

$$P/(M_0\sqrt{D/t})=16K_N\sqrt{\pi/1.5D_d/D} \qquad (6)$$

where, $K_N=\sqrt{3/4}$: Eq. (2) for present end condition

Global Bending Damage

Assuming that the amount of the local dent is small and the reduction of the bending stiffness in the local dent region is negligible in this case, the global bending deformation can be estimated by Eq. (3).

$$P=48EI/L^3w \qquad (7)$$

2) Criterion of the plastic hinge mechanism:

As the lateral load increases, the damage deformation continues according to the pure damage mode until the plastic hinge mechanism is appeared.

However, due to the presence of the local denting damage at the point of the applied, the fully plastic bending capacity may be reduced. Also, the axial forces develop because of the axially restrained end condition. Thus the plastic collapse mechanism of the tube may take place at the lower load level than the case of the pure global bending mode.

For the axially restrained tubular member with the local dent damage, the following empirical expression of the collapse load P_0^* emerges

$$P_0^* = \alpha \cdot P_0 \qquad (8)$$

where P_0 is the collapse load of the tube with the axially free end condition, in which no local denting damage is existed ($P_0 = 4\sigma_0 D^2 t/L$) and α is a reduction factor which is due to the presence of the axial force as well as the local denting damage and is empirically given in terms of L/D and D/t ratios, based upon the experimental results conducted in the present study as

$$\alpha = 0.013L/D - 0.005D/t + 0.6 \qquad (9)$$

Consequently, the criterion for the occurrence of the plastic hinge mechanism reads

$$P \geqq P_0^* \qquad (10)$$

Thus, if Eq. (10) is satisfied for the tubular member under consideration, the plastic collapse mechanism is supposed to be formed,

3) At the large displacement range after the plastic collapse mechanism is formed:

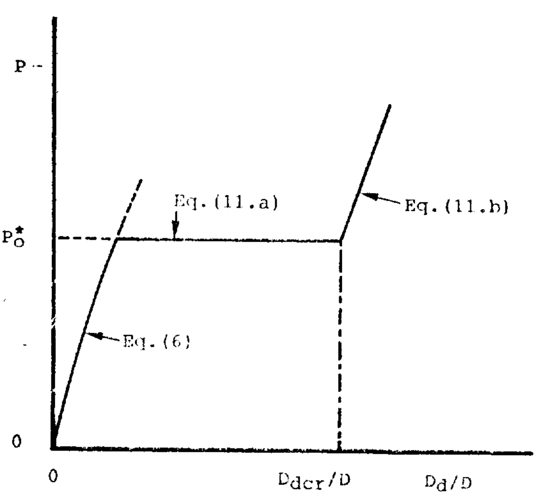

Fig. 9 The schematic configuration of the load-local dent damage relation

Local Denting Damage

According to the experimental results as described in section 4 the stiffness for the local denting deformation is seriously decreased just after the forming of the plastic hinge mechanism but as the global bending deflection increases, the large amount of the axial forces develops. Thus, the resistance for the local denting deformation becomes to be remarkable. The present study suggests the following empirical curve between the load and the local dent depth, based on the experimental result (see Fig. 9)

$$P = P_0^* \qquad ;\ (D_d/D) \leqq (D_{dcr}/D) \qquad (11.a)$$

$$P = P_0^* + K_t \cdot (D_d/D - D_{dcr}/D) \qquad ;\ (D_d/D) > (D_{dcr}/D) \qquad (11.b)$$

where, $K_t = 16K_N \cdot M_0 \sqrt{(\pi/3)(D/t)(D/D_{d0})}$,

$K_N = \sqrt{3/4}$ for present end codition

$D_{dcr}/D = 0.36\exp(-0.027L/D)$,

$D_{d0} = (K_N)^{-2} \cdot (1.5/\pi)(t/256)(P_0^*/M_0)^2$.

Global Bending Damage

Applying the reduced collapse load, P_0^*, the load-global bending deflection relation is obtained from Eq. (5) at the large displacement range, in which the large amount of the axial forces is existed at the plastic hinge.

$$P/P_0^* = \sqrt{1-(2w/D)^2} + (2w/D) \cdot \sin^{-1}(2w/D) \qquad ;\ 2w/D \leqq 1 \qquad (12.a)$$

$$P/P_0^* = \pi w/D \ ;\ 2w/D > 1 \qquad (12.b)$$

where, P_0^* : Eq. (8)

5.2. Accuracy and Applicability of the Proposed Model

As shown in Fig. 10, comparison of damage deformation obtained by the proposed model and the experiment is made so as to verify the accuracy and applicability of the present model.

At the practical range of the damage deformation, both results show good agreement but as damage deformation becomes to be larger with the increasing of the lateral load some discrepancies are appeared. This is due that for the experiment strain hardening

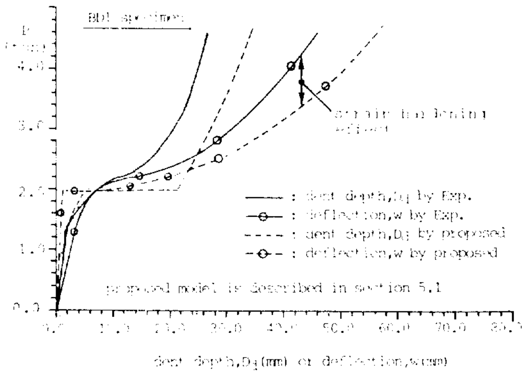

Fig. 10. a Comparison of damage deformation obtained by the experiment and the proposed model for BD1 specimen

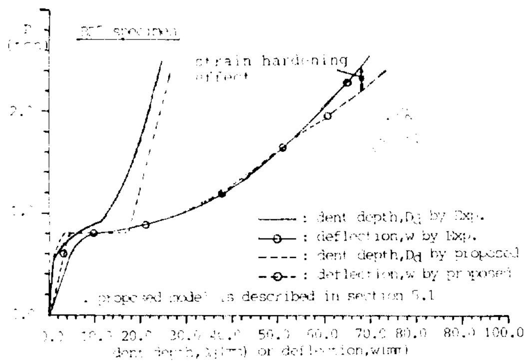

Fig. 10. b Comparison of damage deformation obtained by the experiment and the proposed model for BD5 specimen

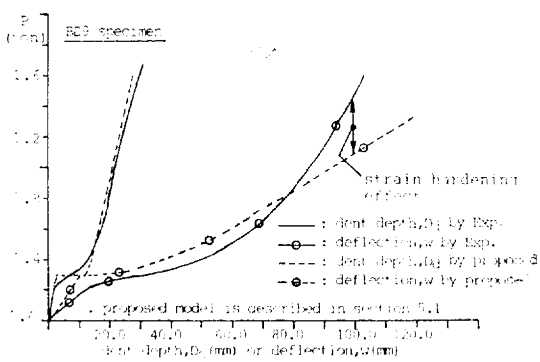

Fig. 10. c Comparison of damage deformation obtained by the experiment and the proposed model for BD9 specimen

effect is automatically incorporated while the proposed model is based upon the rigid perfectly plastic theory.

However, it can be concluded that although the damage deformation characteristics of the tubular member against the accidental load is very complicated, the present model is considered to be able to seek the actual behaviours for the practical purpose.

On the other hand, the energy absorption capability of the member under the accidental loads can be calculated by integrating the area below the load-displacement curve presented in the explicit form, provided that all the energy is dissipated to the member itself.

6. Conclusion

As the first task related to the safety assessment of offshore platforms, the present paper deals with the development of a practical damage estimation model when the rotationally free and axially restrained tubular member is subjected to the accidental loads from collision, falling objects, etc. which can be approximated to the quasi-static problem.

In order to clarify the actual damage characteristics of the member, experiments are conducted for 25 mild steel tubes placed on the typical range of the dimensions.

According to the experimental results, the local denting damage mode and the global bending deformation mode have quite close relations each other.

In particular, the local denting deformation increases seriously just after the plastic hinge mechanism of the member is formed in which the bending moment is dominant but at the large bending deflection range since the large amount of the axial forces is produced from the axially restrained end condition the increasing rate of the local dent deformation is rapidly reduced.

On the other hand, due to the presence of the local denting damage as well as the action of the axial forces the plastic hinge mechanism of the member takes place at quite lower load level rather than the case of the pure global bending mode. Also, since with the increasing of the bending deflection, the axial forces become to be larger, the global bending deformation is resisted.

Based upon the experimental results as well as the existing theoretical model, a new practical damage estimation model is proposed.

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