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Damage on Offshore Tubular Bracing Members

Endommagements de renforcements tubulaires

Schaden an Rohrelementen von »Offshore« - Bauten

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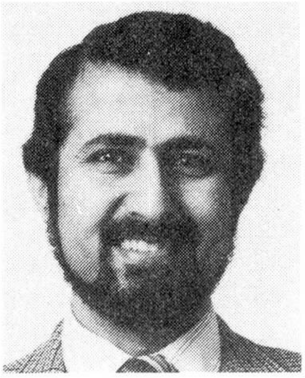

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SUMMARY

This paper deals with the analysis of collision and impact effects on circular tubular beam-columns and offshore bracing members. Methods for estimating the possible extent of damage and its effect on member strength are developed and compared to available theoretical and experimental results. Finally, it is recommended that the simplicity and explicitness of the developed analytical expressions make them ideal for use in design.

RÉSUMÉ

Cet article traite de l'analyse des effets résultant de la collision et des impacts sur une colonne circulaire rigide et les membrures de renforcement d'une structure marine. Les méthodes d'estimation de l'extension possible des dommages et leurs effets sur l'intégrité des membrures, sont developpées et comparées avec les résultats expérimentaux et théoriques. La simplicité des expressions analytiques developpées rendent celles-ci idéales pour le calcul et le projet.

ZUSAMMENFASSUNG

Die Einwirkungen von Kollisionen und Anstößen an Rohrelementen und deren Verstärkungen für »Offshore«-Bauten werden untersucht. Methoden zur Abschätzung möglicher Schäden und der resultierende statische Verlust wurden entwickelt und mit experimentalen Resultaten verglichen. Die Einfachheit der vorgeschlagenen Berechnung spricht für deren Anwendung im Entwurf.

1. INTRODUCTION

The capability of assessing the effects of an impact between a moving object and a structural component of an offshore installation is of considerable interest to design engineers. The task is twofold; first to determine the probable extent of damage and second to evaluate the deterioration in the load-carrying capacity of the member.

So far as the first is concerned, it is a somewhat intractable problem for general design, since the extent of the damage is a function both of the kinetic energy of the impacting body and of the precise local geometry and material characteristics of the zones of impact of the moving object and the structural member. The consequences of the damage can be assessed completely only if these parameters of the damage zone can be exactly defined. A mathematical analysis of the process would require the modelling of the non-linear dynamic, geometric and material behaviours of both bodies. This is a formidable task and not one to be undertaken at the design stage, especially when the impacting objects can range from a valve body dropped from the platform deck, to a supply boat moving at an indeterminate velocity.

However, despite this analytical intractibility the offshore engineer needs to have some information on the damage tolerance of the structural members. He needs, for example, to make decisions prior to construction, regarding the need to protect the structure or to provide alternative, and possibly expensive load paths to cover the case of collision disabling a vital structural member. Guidance should be available to engineers to assess if, in the event of damage occurring, the structural strength has been seriously impaired. Such guidance appears to be lacking in presently available design codes [1,2].

Some line of approach must therefore be developed which adequately fulfills the requirement for information but which circumvents the complexity of precise mathematical formulation. The first task in such a development is to define the precision with which the information is required. In the general situation impact with an object of a certain shape and kinetic energy, for example the bow or side of a vessel, can cause either complete destruction, moderate damage or slight damage to the structural component under consideration. In the first of these categories if such an impact is likely, it will be necessary to provide protection or an alternative load path. In the second, the main concern will be to estimate the reduction in strength and to ensure that the structure can survive until the necessary repairs are effected. In the last category the question may be whether repair is really necessary, or does the damaged structure possess adequate reserve load-carrying capacity to continue being of service. Of course in jackets with a multiplicity of members, one or more of these members may be damaged in one or more of the above ways.

In this paper we restrict our attention to a discussion of the appropriate level of analysis for supplying adequate information to cope with slight to moderate damage. The particular structural component considered here is a circular tubular member, such as may be used in a braced jacket structure. It is shown that approximate and simple methods of analysis can furnish information of significance to engineers, and certainly sufficient for the evaluation of the likely safety of the structural members under consideration.

It is suggested that this level of analysis is one of the most likely to be successful in providing general information to designers. This is not to say that there is no need for more precise mathematical models. However, these may be expensive and may not provide information in an easily accessible and explicit form. Moreover, they can be developed only for special cases and research programmes [3,4,5]. As such they could provide a useful back-up and verification for simplified approaches like the one proposed in this paper.

2. EXTENT OF DAMAGE

Tubular members subjected to lateral loads as a result of impact or collision develop two main modes capable of absorbing the imparted energy. These are local denting of the tube wall and overall bending of the member as a beam. Experimental observations reported in reference [10] indicate that simply supported tubes subjected to lateral knife edge loads, initially undergo a purely local denting phase, followed by overall bending and some additional local denting deformations, until finally collapse occurs. It appears therefore to be useful from the analytical point of view to consider the two modes separately.

2.1 Local Denting Damage

The experimental results from reference [10] indicate that during the initial local denting phase there is a monotonic non-linear increase in lateral load, P, with respect to the local dent depth, d_d. In addition, the deflected profile in the longitudinal direction of the tube, shown in Figures 1 and 2, can be expressed as

$$d = d_d\, e^{-1.3 \frac{x}{D}} \qquad (1)$$

where d is the radial deformation at a distance x from the point of application of the lateral load. As this radial deformation becomes less than 1% of the dent depth, d_d, when x/D>3.5, it appears reasonable to assume that the extent of denting in the longitudinal direction, ℓ_d, is approximately equal to

$$\ell_d = 3.5\, D \qquad (2)$$

on either side of the point of application of the lateral load, as shown in Figure 1(a).

Assuming a rigid perfectly plastic response, the relationship between this lateral load and the dent depth can be shown, through energy considerations [9], to take the form

$$P = K\, m_p \left(\frac{d_d}{D} \right)^{1/2} \qquad (3)$$

where K is a constant and m_p is the plastic moment resultant of the tube wall, given by

$$m_p = \frac{1}{4} \sigma_Y t^2 \qquad (4)$$

Experimental results reported in references [5,9] and plotted in Figure 3, verify the validity of eqn (3), and in addition indicate that constant K is approximately given by

$$K \simeq 150 \qquad (5)$$

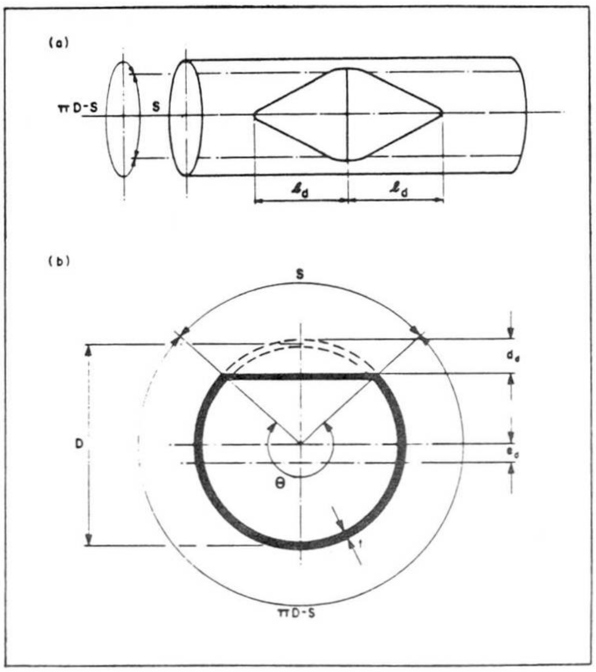

Fig. 1 Dent geometry

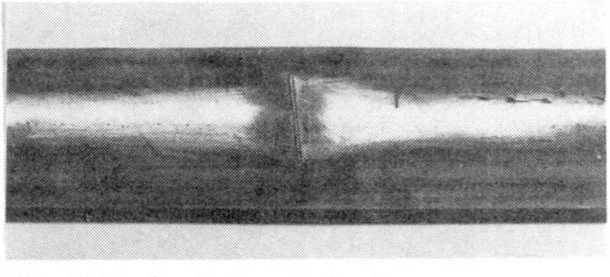

Fig. 2 Typical local dent

With the load-dent depth response and the locally deformed shape now defined it is possible to estimate the amount of energy absorbed locally. The experimental results reported in reference [10], and similar results reported in [5,9], indicate that in general the deformed shape consists of a very well defined yield line under the indenter (through which the lateral load is applied); the remainder of the deformed shape has no well defined yield lines, as shown in Figure 2. Assuming that the imparted energy is dissipated locally, and that the denting process takes place at a sufficiently slow rate, to allow the replacement of the impact force by a pseudo-static load, the energy absorbed during the formation of the local dent, E_d, may be expressed as follows

$$E_d = \int P \, d(d_d) \qquad = 100 \, m_p \left(\frac{d_d^3}{D}\right)^{1/2} \tag{6}$$

While the tube continues to deform into the local denting mode its stiffness against overall bending deformations decreases continually, due to the change in the tube's cross-section, as shown in Figure 1(b). At a certain critical value of the lateral load, P_o, this reduced bending stiffness will reach a certain value after which the tube will start deforming in an overall bending mode. During this second stage it is assumed that local denting ceases to increase further and that the remainder of the imparted energy is absorbed by the reduced section tube deforming plastically into this overall bending mode.

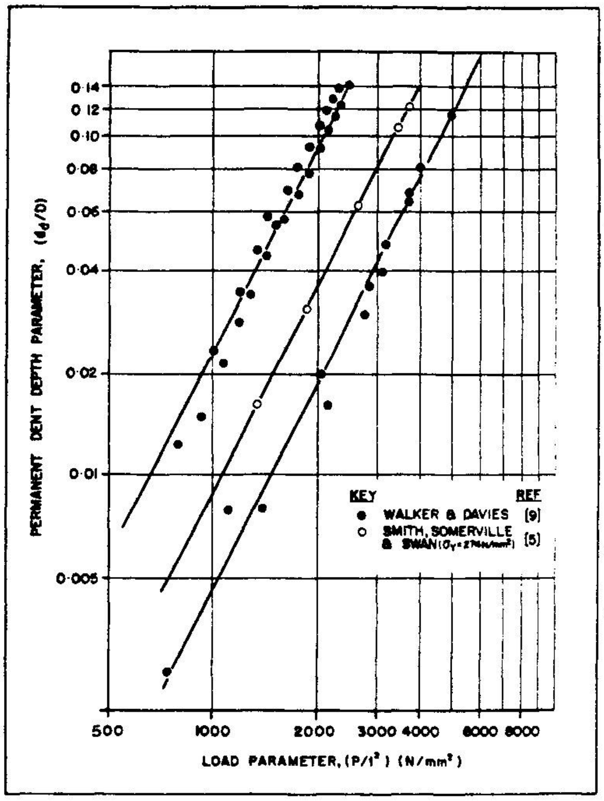

Fig.3 Dependence of dent depth on lateral load

2.2 Overall Bending Damage

The extent of overall bending damage of a tubular member subjected to lateral impact loads depends strongly on the geometry of the member and its exact end support conditions. Clearly, tubes with built-in ends develop considerably smaller overall deformations than pin-ended tubes. Extensive theoretical treatment of the problem is presented in references [7,8].

However, for reasons of simplicity and as a conservative approach, it is assumed here that the tube is fully restrained flexurally at its end supports, but free to translate in the longitudinal direction. This ensures that no longitudinal tensile stresses are induced due to pull-in at the supports as a result of overall bending deformations. Under such conditions the maximum lateral load, P_o, may be obtained using classical limit plasticity theory. This shows that

$$P_o = \frac{8 M_p}{L} \tag{7}$$

where M_p is the plastic moment capacity of the tube's cross-section. For an undamaged circular tubular member

$$M_p = D^2 t \, \sigma_Y \tag{8}$$

For the locally dented section, shown in Figure 1, M_p becomes a function of dent depth d_d. The following approach is employed in order to obtain the required relationship between M_p and d_d. It is first assumed that a certain initial longitudinal compressive stress, σ_{pd}, needs to be applied at the damaged part of the tube's cross-section, shown as arc S in Figure 1(b), before plastification occurs and a hinge is formed. This has been shown in references [4,6] to take the form

$$\sigma_{pd} = \sigma_Y \left(\frac{D}{t}\right) \left[\sqrt{\frac{16}{9}\left(\frac{d_d}{D}\right)^2 + \left(\frac{t}{D}\right)^2} - \frac{4}{3}\left(\frac{d_d}{D}\right) \right] \tag{9}$$

Once σ_{pd} has been exceeded in the damaged fibres, they become ineffective and any additional bending is carried by the remaining effective section, shown as arc (πD-S) in Figure 1(b). Considering the bending equilibrium of this fully plastic effective section enables the reduced plastic moment M_{pd} to be obtained as

$$M_{pd} = M_p\,[\cos\beta - \beta] \qquad (10)$$

where

$$\beta = \left(\frac{d_d}{D}\right)^{\frac{1}{2}}\left[1 - \frac{\sigma_{pd}}{\sigma_Y}\right] \qquad (11)$$

The maximum lateral load, P_{od}, that can be carried by the flexurally restrained tube that has been locally dented at the middle, can be obtained by the following modified version of eqn (7), as a function of the dent depth, d_d.

$$P_{od} = \frac{4\,M_p}{L}\left[1 + \frac{M_{pd}}{M_p}\right] \qquad (12)$$

In obtaining eqn (12) it has been assumed that the plastic hinges at the end supports can develop their full moment capacity, M_p, while the hinge formed at the position of the dent can only reach M_{pd}. When d_d=0 eqn (12) reverts to the form of eqn (7).

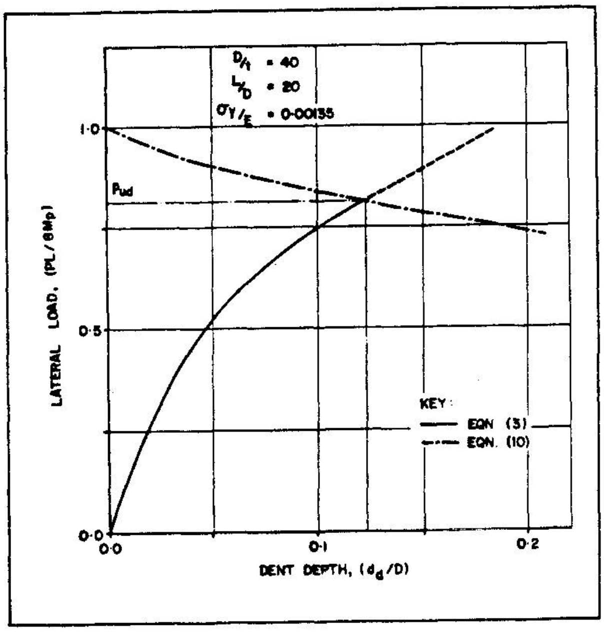

Fig.4 Estimation of ultimate lateral load, P_{ud}

The ultimate lateral load, P_{ud}, that can be sustained by the dented tube may be obtained by solving simultaneously eqns (3) and (10), as shown in Figure 4. For a bracing member with D/t=40, L/D=20 and σ_Y/E=0.00135

$$P_{ud} = \frac{6.6\,M_p}{L}$$

The maximum dent depth, $\bar{d}_d$, suffered by this tube before it starts deflecting laterally is shown in Figure 4 to be

$$\frac{\bar{d}_d}{D} = 0.12$$

Although this simple approach enables the estimation of the extent of local damage and the evaluation of the ultimate lateral load carrying capacity of the damaged tube, it does not give any information on the extent of lateral deformations. The assumptions on which the present analysis is based imply that when P_{ud} has been reached the tube will cease deforming locally and will start displacing laterally at the same load. The magnitude of this lateral displacement, d_o, may be obtained by considering the energy absorption characteristics of the beam mechanism. The energy, E_o, absorbed by the flexurally restrained locally dented beam which, according to limit plasticity, collapses by the formation of a three hinge beam mechanism, is given by

$$E_o = \frac{4\,M_p}{L}\left[1 + \frac{M_{pd}}{M_p}\right] d_o \qquad (13)$$

The overall bending displacement, d_o, may then be obtained by assuming that the kinetic energy, E_k, released in the course of a collision or impact is absorbed by the tube developing deformations in both the local denting and overall bending modes, so that

$$E_k = E_d + E_o \qquad (14)$$

substituting eqn (13) into eqn (14) allows d_o to be expressed as

$$\frac{d_o}{L} = \frac{(E_k - E_d)}{4\,(M_{pd} + M_p)} \qquad (15)$$

2.3 Applicability

The very simple methods developed in sections 2.1 and 2.2 allow the estimation of the extent of damage in both the local denting and overall bending modes, as well as the energy absorption characteristics of a tubular member. One of the basic assumptions used is that the tube is sufficiently compact to develop its full plastic moment capacity and therefore allow the use of plasticity methods of analysis. Guidance on geometries that can be considered compact is given in references [1,2]. However, even in cases where these geometric limitations are exceeded the present analysis may still be used in a modified form in which the material yield stress, σ_Y, is replaced by an effective limit stress equal to the local buckling stress of the section as defined in references [1,2].

In the general case a member in a braced frame is elastically restrained at its ends against both flexural rotations and longitudinal displacements. In such situations more accurate results may be obtained by using more complicated forms of analysis, in which the membrane stresses induced in the member due to the restraint against pull-in at the supports, are taken into account. This is particularly important when estimating overall bending damage. Relevant information is given in references [7,8]. However, the general approach employed in sections 2.1 and 2.2 is still applicable, and will certainly result in upper bound estimates of the extent of damage.

3. EFFECT OF DAMAGE ON MEMBER STRENGTH SUBJECT TO AXIAL COMPRESSION

The effect of local denting of the tube wall is to cause a reduction in the effective section area and modulus and an eccentricity of the neutral axis over the locally damaged region. Taken with accompanying overall bendin deformations, their combined effect can result in rapid deterioration in the load-carrying capacity of the member. Several methods have been proposed for assessing the reduced strength of damaged members, mostly dealing with the effects of local denting [4] or overall bending [3,5] in isolation. The combined effect of such damage modes on tubular member strength has been examined analytically in a recent paper [6], the important features of which are summarised here.

It is assumed that the stresses initially induced by the application of a small axial load are carried in the dented zone, shown as arc S in Figure 1(b), mainly by bending action, which rapidly leads to the formation of a hinge at the middle of the dent, as shown in Figures 1(a) and 2. These initial plastification stresses, σ_{pd}, are given by eqn (9). The consequent loss of stiffness makes this damaged zone ineffective in carrying additional axial load. Moreover, as the bending stiffness of the damaged tube is mainly controlled by that of the reduced effective section, shown as arc (πD-S) in Figure 1(b), this reduced effective stiffness may be considered to determine the loading response of the whole member. In addition, the axial load, which is still applied at the centroid of the full section, acts through an eccentricity, e_d, with respect to the neutral axis of the reduced effective section, shown in Figure 1(b).

The effects of overall bending damage are assumed to be similar to those resulting from large initial overall imperfections, and in the ensuing analysis they are treated as such.

These assumptions lead to a simplified analysis in which the damaged member is treated as a beam-column with a reduced effective stiffness. Its ultimate strength, σ_{ud}, may then be obtained by considering a first yield collapse criterion and using simple beam-column analysis, similar in form to that employed in deriving the design recommendations in reference [1]. This can be shown [6] to lead to the following quadratic expression in terms of σ_{ud}

$$\frac{1}{\sigma_e}\sigma_{ud}^2 - \left[1 + \alpha_o\lambda_d + \frac{A_d e_d}{Z_d} + \frac{f_Y}{\sigma_e}\right]\sigma_{ud} + f_Y + \sigma_{pd}\frac{A_d e_d}{Z_d} = 0 \tag{16}$$

where f_y is the average squash stress of the damaged section given by

$$f_Y = (\sigma_Y - \sigma_{pd})\frac{A_d}{A} + \sigma_{pd} \tag{17}$$

and σ_e is the overall critical stress, which for a tubular member is given by

$$\sigma_e = \frac{\pi^2 E D^2}{8 L^2} \tag{18}$$

Parameters α_o and λ_d are respectively the overall imperfection parameter and the slenderness ratio, which for a damaged member take the form [6]

$$\alpha_o = \sqrt{2}\frac{d_o}{L} - 0.001 + 0.875\frac{\sigma_Y}{E} \tag{19}$$

and $$\lambda_d = \frac{L}{r_d} - 0.2\pi\sqrt{\frac{\sigma_Y}{E}} \tag{20}$$

The reduced effective section cross-sectional area, A_d, section modulus, Z_d, neutral axis eccentricity, e_d, and radius of gyration, r_d, may be obtained from

$$\left.\begin{aligned} A_d &= \frac{1}{2} D t \theta \\ Z_d &= \frac{r_d^2 t \theta}{[1 - \bar{d}_d/D + 2 e_d/D]} \\ e_d &= D\frac{\sin(\theta/2)}{\theta} \\ r_d &= \frac{D}{2}\left\{\frac{1}{2}\left[1 + \frac{\sin\theta}{\theta} - 8\frac{\sin^2(\theta/2)}{\theta^2}\right]\right\}^{1/2} \end{aligned}\right\} \tag{21}$$

where θ is the angle subtended by arc ($\pi D - S$) to the centre of the tube, shown in Figure 1(b), and it is given in terms of the dent depth, $\bar{d}_d$, by

$$\theta = 2\pi - 2\sin^{-1}\left[2\sqrt{\frac{\bar{d}_d}{D}\left(1 - \frac{\bar{d}_d}{D}\right)}\right] \tag{22}$$

Thus the ultimate strength, σ_{ud}, of a damaged circular tubular member may be obtained using eqns (16) to (22).

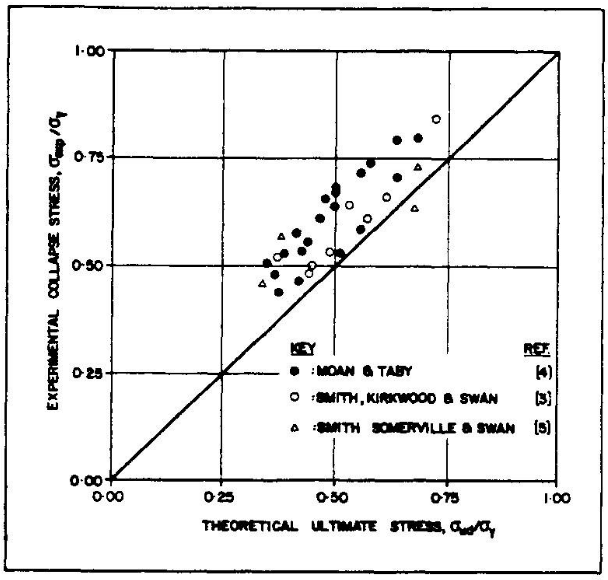

Fig.5 Theoretical and experimental comparisons for damaged tubes

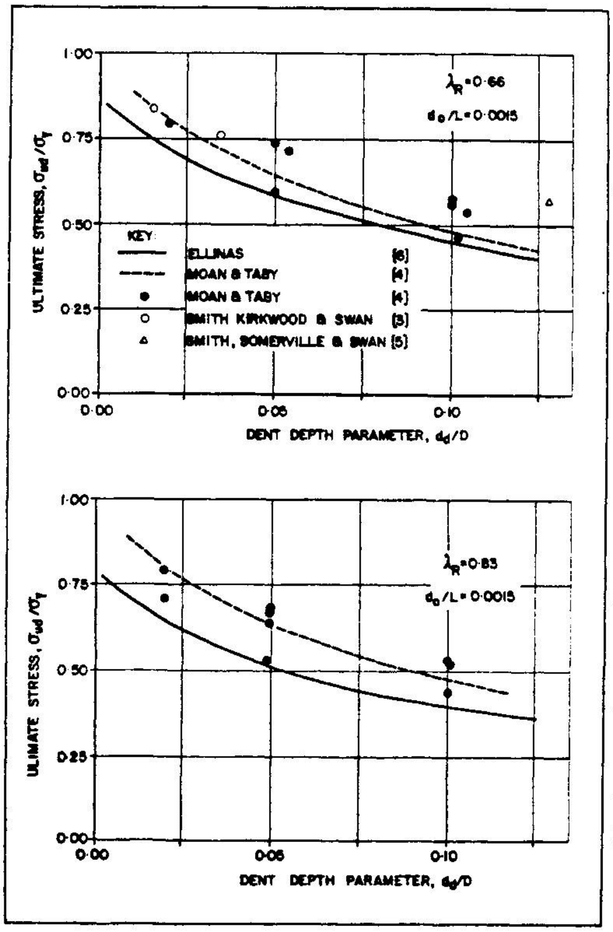

Fig.6 Comparisons for tubes with local denting damage only

4. THEORETICAL AND EXPERIMENTAL COMPARISONS

Available experimental information on the behaviour of axially loaded damged tubular columns is limited to a number of test results reported in reference [3,4,5], obtained mainly from locally dented steel specimens with geometries in the ranges $30<D/t<90$ and $0.6<\lambda_R<1.1$. For circular tubular members the reduced slenderness parameter, λ_R, is given by

$$\lambda_R = \frac{L}{D}\frac{2\sqrt{2}}{\pi}\sqrt{\frac{\sigma_Y}{E}} \tag{23}$$

Comparisons between predictions from the present theoretical method and available test results are shown in Figure 5. It is evident that a close agreement exists

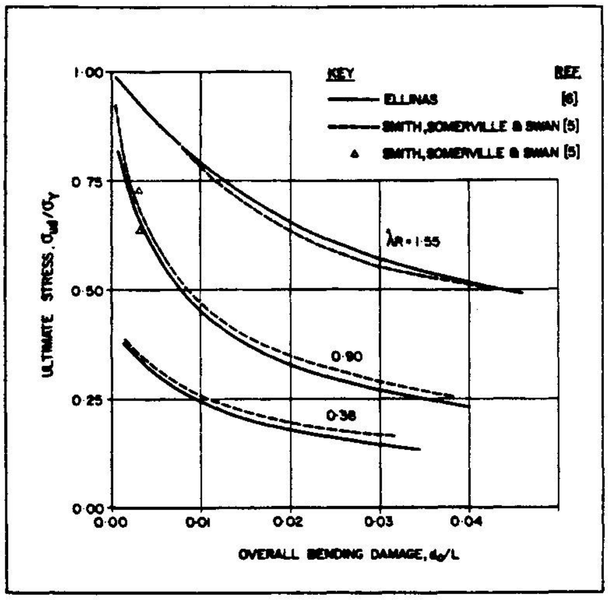

Fig.7 Comparisons for tubes with overall bending damage only

with the theory described in section 3 providing safe lower bounds to the experimental scatter. The single test result that lies below the theoretical line corresponds to a specimen reported in reference [5] to contain overall bending damage only, that might, however, have been locally dented before testing.

Further comparisons are shown in Figure 6 for tubes that contained local denting damage only. Theoretical results from reference [4] are also presented. It is again clear that the present method provides predictions in excellent agreement with those from reference [4] and with available test results.

Finally, comparisons with experimental and theoretical results from reference [5], for tubes with overall bending damage only, are shown in Figure 7. Again a close correlation appears to exist.

The theoretical and experimental comparisons of Figures 5,6, and 7 provide a convincing confirmation of the validity of the present simplified analysis in predicting the behaviour of damaged tubular member, subject to axial compression.

5. CONCLUSIONS

The methods developed in this paper for estimating the likely extent of damage in circular tubular bracing members due to accidental collision or impact, and for evaluating its effects on member strength, are based on simple physical reasoning and observed experimental behaviour. They lead to simple straightforward, analytical formulations, at a level sufficiently explicit to be of use to engineers who, faced with a damage problem, need to assess its consequences and make design or repair decisions.

The excellent agreement between predictions obtained from the present theory and available experimental and theoretical results, combined with the demonstrated lower-boundedness of the method, provide strong verification of its validity in predicting damaged member behaviour.

It is hoped that the methods presented goes some way in aurgmenting existing knowledge and in providing much needed guidance on the damage tolerance of circular tubular bracing members. Their simplicity and explicitness should make them ideal for use in design situations.

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The authors wish to acknowledge the help given by J P KENNY personnel in the preparation of this paper.

NOTATION

A, A_d	area of full and reduced effective section respectively
d, d_d, $\bar{d}_d$	dent depth
d_o	overall bending damage
D	tube mean diameter
e_d	eccentricity of centroid of reduced effective section from that of full section

E	modulus of elasticity
E_d	energy absorbed in local denting mode
E_k	kinetic energy released after impact
E_o	energy absorbed in overall bending mode
f_Y	average squash stress of damaged section
l_d	extent of denting in longitudinal direction
L	tubular member length
m_p	plastic moment resultant of tube wall
M_p	plastic moment capacity of full section
M_{pd}	plastic moment capacity of damaged section
P	applied lateral load
P_o	maximum lateral load sustained by undamaged beam
P_{od}	maximum lateral load sustained by local dented tubular beam
P_{ud}	ultimate lateral load sustained by locally dented tubular beam
r_d	radius of gyration of reduced effective section
t	tube wall thickness
x	longitudinal direction
Z_d	elastic section modulus of reduced effective section
α_o	imperfection parameter
β	overall bending damage parameter
θ	angle subtended by the reduced effective section to the centre of the tube
λ_d	column slenderness ratio of the reduced effective section
λ_R	reduced column slenderness parameter
σ_e	overall critical stress
σ_{pd}	dent plastification stress
σ_{ud}	ultimate axial stress carried by damaged column
σ_Y	yield stress

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