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# Structural Characteristics of Damaged Offshore Tubular Members

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**KEY WORDS:** Damaged tubular members, Ultimate bending capacity, Denting force, Dent deepening rate, Denting test, Bending test

**ABSTRACT:** *Over the past few decades various experimental and theoretical investigations have been performed on offshore tubular members with regard to damage resistance and residual strength. Analysis of damaged tubular members requires a three-dimensional shell analysis for accurate results. Even though various commercial packages are available for this purpose, a beam-column analysis is preferred for offshore structural designs. In this paper, empirical equations are provided for a more accurate beam-column analysis of damaged tubes including the relationships between the lateral denting load and the depth of the dent, the rate of dent deepening due to increasing curvature and the longitudinal variation in the dent depth of damaged tubes. A design equation to predict the ultimate bending capacities of damaged offshore tubular members is also presented.*

## 1. Introduction

Drilling of deep sea oil and gas poses many problems that are insignificant in calmer shallow waters. The collision of a ship with an offshore structure is among the potential problems (Donegan, 1982) and the probability of the event and its likely effects must be considered. The risk of a collision is significant for floating as well as fixed rigs since the elements of floating rigs tend to be thin due to the inherent weight savings for the requirement of a floating design.

A collision with an offshore platform can be categorized as a major or minor event based on the extent of the damages to the structure. A minor collision results in local repairable damage to the structure and usually does not disrupt operation. On the other hand, a major collision will cause global damage to the platform and will certainly require operational shutdowns. In reality, the probability of major collisions is maintained at a low level by adequate preventive measures.

The precautionary safety measures adopted in the North Sea include 500 m radius of safety zone, marking these zone for permanent platforms on navigation charts, identification of the installations and others (Mavrikios and de Oliveira, 1983). Provided that the probability of major offshore collisions can be kept at a low level and that due considerations are taken to protect human life, efficient design of offshore structures so that they are able to withstand minor collisions is an important problem to be solved.

An ISSC report (Jensen et al., 1997) summarized analytical methods to predict the residual strengths of damaged tubes proposed by Taby et al. (1981), Smith et al. (1981) and Cho (1989). In this report, a summary of experimental investigations on damaged tubes subjected to axial compression, bending moment, combined axial compression and bending moment and combined axial compression and hydrostatic pressure is also provided. Comparison of the design formulations proposed to predict the residual strengths of damaged tubes are also included in the report.

Recent research on damaged tubes is very rare. However, several researchers performed theoretical and experimental investigations with undamaged tubes subjected to large deformation pure bending. Elchalakani et al. (2002a) investigated the collapse mechanism of slender circular tubes under pure bending. They obtained an expression for the plastic collapse moment by equating the total energy absorbed in bending, rolling and ovalization to the external work. Elchalakani et al. (2002b) proposed a design-oriented treatment for circular steel tubes of varying $D/t$ ratios to predict the moment-rotation response under pure bending. Jiao and Zhao (2004) proposed section slenderness limits of very high strength circular steel tubes in bending.

Efficient design of offshore structures with the ability to withstand minor collisions requires methods for predicting the extent of damage to the structure due to collisions and the residual strength of the damaged structure. A non-linear shell analysis is necessary for more accurate estimation of

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damage and residual strength. Currently, there are various commercial shell analysis packages available, but they are not widely used because most offshore structural designers prefer to perform beam or beam-column analyses.

The major difficulty in beam or beam-column analysis of offshore collisions lies in the consideration of the shell effects. In this paper, experimental results are summarized in the form of design equations used to quantify the relationships between the lateral denting load and depth of the dent, and between the rate of dent deepening and the curvature increment. The first relationship can be utilized to predict collision damage and the second relationship is useful in analyzing the residual strengths of damaged tubes. A design equation to predict the ultimate bending capacity which can be used to derive design formulations of loading component interaction type is also presented in this paper.

## 2. Experimental Procedures

Two series of experiments in which tubes typical of offshore construction are subjected to a static lateral load followed by a pure bending moment are described.

### 2.1 Test models

Thirty test models with lengths of 1,100 mm were prepared from 6-m tubes manufactured by electric resistance welding. The thickness and outside diameter of each model were measured six times at different locations. Material properties including the yield stress and Young's modulus were obtained from tensile tests. The tensile test coupons were cut from the parent tubes and their yield stress was determined as the 0.2% proof stress.

In Table 1, the thickness, outside diameter, Young's modulus and yield stress of each model are summarized. The values listed in the table are the averages of the measurements. The diameter to thickness ($D/t$) ratios in this study ranged from 20 to 45, representative of actual structures. The yield stress ranged from 290 to 420 N/mm$^2$, which is also believed to represent the yield stresses of real-world structures. The Young's modulus for the series O models is lightly lower than those of the other series.

### 2.2 Denting tests

Denting tests were performed on 23 unstiffened tubes in order to investigate the resistances of the tubes against a lateral denting force. The geometry and material properties of each test model are presented in Table 1, which also includes undamaged models.

In the test, a wooden pad was inserted under the model at the location of the lateral load application. The downward displacement of the damaged side was measured by two dial gauges and the two readings were averaged. The displacement of the opposite side was measured by one dial gauge.

The denting depth was estimated as the difference between the two displacement values. The indenters had various breadths and included a sharp knife edge. In Table 2, the maximum denting force and maximum denting depth together with the residual denting damage obtained after removing the lateral load are shown. The breadth of the indenter is also provided in Table 2.

The non-dimensional dent damage ($\delta_d = d_d/D$) ranged from 0.070 to 0.400. As seen in Table 2, the elastic spring-back of

**Table 1** Geometries and material properties of the test models

| Model | Thickness (mm) | O.D. (mm) | $E$ (GPa) | $\sigma_Y$ (MPa) |
|---|---|---|---|---|
| J1 | 2.35 | 48.72 | 216 | 414.3 |
| J2 | 2.34 | 48.71 | 216 | 414.3 |
| J3 | 2.37 | 48.70 | 216 | 414.3 |
| J4* | 2.37 | 48.70 | 216 | 414.3 |
| J5* | 2.35 | 48.73 | 216 | 414.3 |
| K1 | 2.31 | 48.72 | 197 | 382.4 |
| K2 | 2.31 | 48.72 | 197 | 382.4 |
| K3 | 2.25 | 48.70 | 197 | 382.4 |
| K4 | 2.27 | 48.75 | 197 | 382.4 |
| K5* | 2.35 | 48.75 | 197 | 382.4 |
| L1 | 1.44 | 50.72 | 189 | 312.1 |
| L2 | 1.44 | 50.75 | 189 | 312.1 |
| L3 | 1.45 | 50.69 | 189 | 312.1 |
| L4 | 1.46 | 50.68 | 189 | 312.1 |
| L5 | 1.47 | 50.72 | 189 | 312.1 |
| M1 | 1.47 | 50.66 | 194 | 290.9 |
| M2 | 1.44 | 50.74 | 194 | 290.9 |
| M3 | 1.48 | 50.75 | 194 | 290.9 |
| M4 | 1.45 | 50.77 | 194 | 290.9 |
| M5* | 1.45 | 50.72 | 194 | 290.9 |
| N1 | 1.47 | 60.40 | 186 | 330.7 |
| N2 | 1.44 | 63.47 | 186 | 330.7 |
| N3 | 1.46 | 63.50 | 186 | 330.7 |
| N4 | 1.46 | 63.48 | 186 | 330.7 |
| N5* | 1.48 | 63.50 | 186 | 330.7 |
| O1* | 1.49 | 63.45 | 180 | 306.1 |
| O2 | 1.46 | 63.51 | 180 | 306.1 |
| O3* | 1.45 | 63.50 | 180 | 306.1 |
| O4 | 1.44 | 63.54 | 180 | 306.1 |
| O5 | 1.44 | 63.59 | 180 | 306.1 |

note: * indicates undamaged models

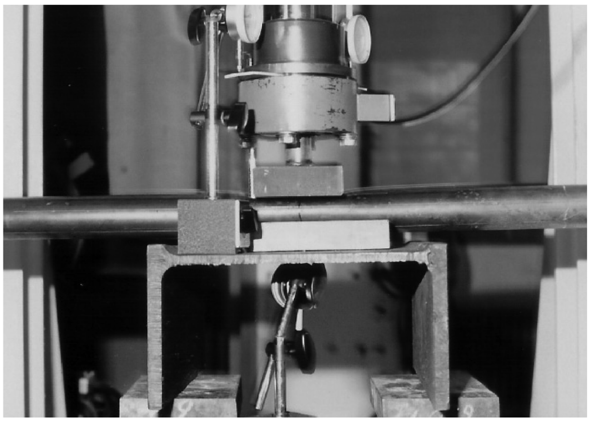


**Fig. 1** Denting test performed on unstiffened tubes

**Table 2** Results of the denting tests

| Model | $B/D$ | Denting force (KN) | Depth of dent, $d_d$ (mm) | |
|---|---|---|---|---|
| | | | Max. | Residual |
| J1 | 0 | 18.85 | 6.65 | 5.81 |
| J2 | 1.03 | 23.61 | 7.42 | 6.28 |
| J3 | 0 | 27.52 | 14.79 | 13.8 |
| K1 | 1.03 | 28.35 | 15.67 | 14.68 |
| K2 | 0 | 23.48 | 13.93 | 12.86 |
| K3 | 2.05 | 27.60 | 10.85 | 9.64 |
| K4 | 2.05 | 33.88 | 16.79 | 15.96 |
| L1 | 0 | 6.92 | 7.78 | 6.69 |
| L2 | 0.99 | 7.43 | 9.55 | 7.65 |
| L3 | 0 | 12.26 | 21.13 | 20.28 |
| L4 | 0.99 | 9.16 | 12.66 | 10.83 |
| L5 | 1.97 | 9.06 | 11.04 | 8.67 |
| M1 | 0.99 | 10.62 | 19.97 | 18.32 |
| M2 | 0 | 9.60 | 14.75 | 13.54 |
| M3 | 1.97 | 9.60 | 12.73 | 10.49 |
| M4 | 1.97 | 13.04 | 20.86 | 19.25 |
| N1 | 0 | 6.37 | 8.37 | 7.54 |
| N2 | 0.97 | 6.39 | 7.13 | 4.45 |
| N3 | 0 | 11.56 | 24.56 | 22.67 |
| N4 | 1.58 | 9.14 | 12.77 | 9.14 |
| O2 | 0 | 7.60 | 13.96 | 11.59 |
| O4 | 0.79 | 10.78 | 24.69 | 22.22 |
| O5 | 1.57 | 13.07 | 25.75 | 21.67 |

model L3 was about 1.7% and the local denting damage ($\delta_d$) was 0.40. The elastic spring-back cannot be neglected when $\delta_d$ is smaller than 0.35, but can be ignored when the denting damage is greater than 0.35.

### 2.3 Bending tests

Four-point bending tests were conducted on the 23 damaged tubes and the seven undamaged tubes. The purpose of these tests was to collect experimental information regarding the relationship between the bending moment and the curvature.

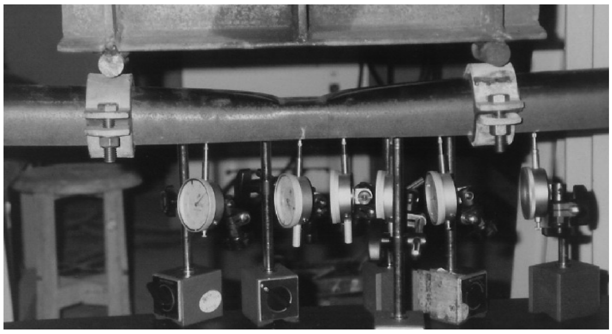


**Fig. 2** Bending capacity test performed on damaged tube

**Table 3** Bending test results

| Model | $D/t$ | $B/D$ | $\delta_d$ | $M_u/M_p$ | $\Phi/\Phi_Y$ |
|---|---|---|---|---|---|
| J1 | 20.73 | 0 | 0.111 | 0.84 | 3.07 |
| J2 | 20.82 | 1.03 | 0.103 | 0.82 | 3.53 |
| J3 | 20.55 | 0 | 0.271 | 0.68 | 4.82 |
| J4 | 20.55 | 0 | 0 | 0.89 | 3.98 |
| J5 | 20.74 | 0 | 0 | 0.82 | 2.06 |
| K1 | 21.09 | 1.03 | 0.229 | 0.58 | 6.04 |
| K2 | 21.09 | 0 | 0.257 | 0.63 | 4.25 |
| K3 | 21.64 | 2.05 | 0.162 | 0.74 | 5.11 |
| K4 | 21.48 | 2.05 | 0.305 | 0.58 | 8.52 |
| K5 | 20.74 | 0 | 0 | 0.86 | 5.28 |
| L1 | 35.22 | 0 | 0.124 | 0.78 | 2.37 |
| L2 | 35.24 | 0.99 | 0.107 | 0.73 | 2.80 |
| L3 | 34.96 | 0 | 0.408 | 0.4 | 6.45 |
| L4 | 34.71 | 0.99 | 0.207 | 0.63 | 3.99 |
| L5 | 34.5 | 1.97 | 0.154 | 0.67 | 4.64 |
| M1 | 34.46 | 0.99 | 0.356 | 0.5 | 8.33 |
| M2 | 35.24 | 0 | 0.261 | 0.59 | 4.01 |
| M3 | 34.29 | 1.97 | 0.182 | 0.65 | 4.21 |
| M4 | 35.01 | 1.97 | 0.37 | 0.48 | 10.15 |
| M5 | 34.98 | 0 | 0 | 0.96 | 1.02 |
| N1 | 41.09 | 0 | 0.065 | 0.77 | 2.85 |
| N2 | 44.08 | 0.97 | 0.061 | 0.77 | 2.36 |
| N3 | 43.49 | 0 | 0.343 | 0.46 | 6.95 |
| N4 | 43.48 | 1.58 | 0.129 | 0.65 | 3.68 |
| N5 | 42.91 | 0 | 0 | 0.88 | 2.52 |
| O1 | 42.58 | 0 | 0 | 0.89 | 2.09 |
| O2 | 43.5 | 0 | 0.156 | 0.71 | 3.72 |
| O3 | 43.79 | 0 | 0 | 1 | 3.51 |
| O4 | 44.13 | 0.79 | 0.352 | 0.49 | 9.46 |
| O5 | 44.16 | 1.57 | 0.36 | 0.47 | 10.06 |

Compressive loads were applied at locations above the clamps, located away from the damaged parts and rubber pads were installed between the model and the clamps. The applied load was controlled by the displacement. The deflections were measured at every load step by six dial gauges located underneath the model (Fig. 2). The minimum outside diameter of the damaged part was also measured using calipers at every loading step. The curvature was estimated using the deflection readings. In Table 3, the ultimate bending capacity of each model is presented together with the corresponding curvature.

In Table 3, the ultimate bending capacity was non-dimensionalized by the fully plastic moment, $Mp$ (= $\sigma_Y tD^2$), of the tube. The curvature values presented in the table are the values when the model reached its ultimate state, non-dimensionalized by the yield curvature, $\Phi_Y$ (= $2\sigma_Y/E/D$). For model N5, which was undamaged, ovalization was observed at both ends of the model when it reached its ultimate state.

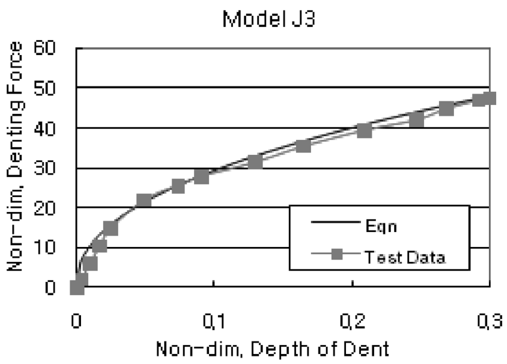
## 3. Denting Force - Denting Depth Relationship

The relationship between the lateral denting force and the denting depth can be used not only for static problems but also for dynamic situations (Cho, 1990). Many researchers have attempted to predict this relationship either analytically (Wierzbicki and Suh, 1986) or empirically (Cho, 1990).

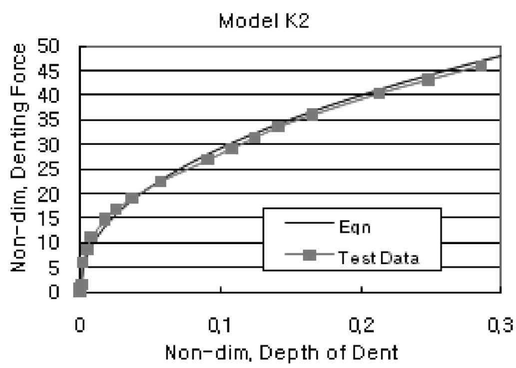
The proposed methods for predicting the relationship are not sufficient for practical use primarily because they only consider knife edge damage. The empirical equation shown below was derived by regression of the results of the denting tests reported in this paper.

$$\frac{F}{m_p} = 2.0\left(\frac{D}{t}\right)^{0.2}\left(\frac{E}{\sigma_Y}\right)^{0.5}\delta_d^{0.45}\exp\left\{0.1\,(B/D)\,\delta_d^{-0.3}\right\} \tag{1}$$

In Fig. 3, the denting damage predicted using Eq. (1) is compared with test data for models J3 and K2 and very good correlations can be observed.




(a) model J3




(b) model K2

**Fig. 3** Comparison of predicted denting damage obtained using Eq. (1) with that obtained experimentally

## 4. Mathematical Expressions for Dent Damage

As mentioned earlier, the three-dimensional shell analysis for damaged tubes is time-consuming. However, beam-column analyses of these problems requires a method that considers shell effects. In order to consider the damaged tube as a beam-column with a varying cross-section, the damaged shape should be reasonably approximated. In this section, mathematical expressions are developed for the damaged cross-section and the longitudinal variation in the dent depth.

### 4.1 Damaged cross-section

In Fig. 4, photographs of the dented part of a damaged tube are shown. Close observations of various models allow for the assumption of the dented cross-section, as shown in Fig. 5 (Frieze and Cho, 1993). When the outside diameter ($D_o$) and non-dimensional dent depth ($\delta_d$) are given, the minimum outside diameter ($D_{dmin}$) can be determined using Eq. (2).

$$\delta_d = 1 - D_{dmin}/D_o \tag{2}$$

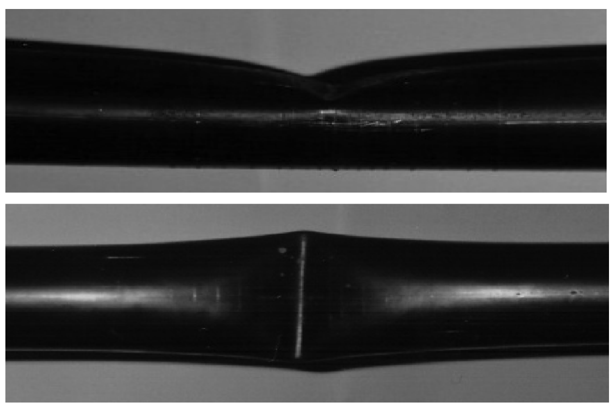


**Fig. 4** Photographs of a dented tube

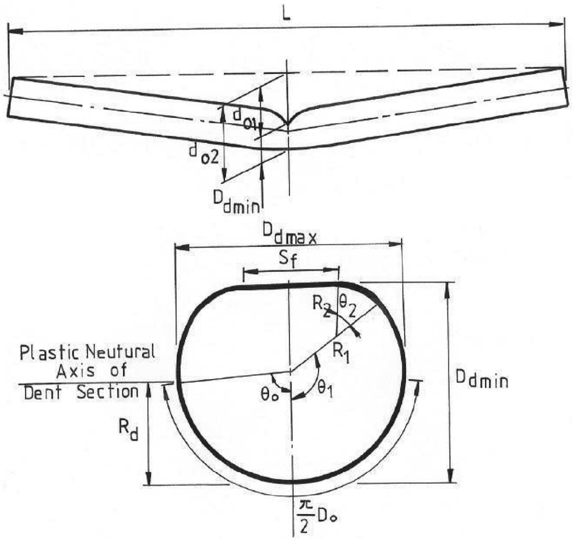



**Fig. 5** Approximation of the damaged tube shape

The maximum outside diameter ($D_{dmax}$) and the width of the flattened segment ($S_f$) then can be obtained using Eqs. (3) and (4), respectively.

$$\frac{D_{dmax}}{D_o} = 1.0 + 2.45\left(\frac{1}{D_{dmin}/D_o} - 1\right)\exp\{-2.4(D_{dmin}/D_o\} \quad (3)$$

$$\frac{S_f}{D_o} = 1.64\left(1 - \frac{D_{dmin}}{D_o}\right)^{0.56}\exp\{0.33(D_{dmin}/D_o)\} \quad (4)$$

With the obtained values of $D_{dmax}$ and $S_f$, $R_1$ and $R_2$ (see Fig. 5) can be calculated using Eqs. (5) and (6), respectively.

$$R_1 = \frac{1}{2}D_{dmax} \quad (5)$$

$$R_2 = (0.5\pi D_o - R_1\theta_1 - 0.5S_f)/\theta_2 \quad (6)$$

$$\theta_1 = \pi\left\{1 - 1.47\left(1 - \frac{D_{dmin}}{D_o}\right)^{0.4}\exp\left(-0.94\frac{D_{dmin}}{D_o}\right)\right\} \quad (7)$$

$$\theta_2 = \pi - \theta_1$$

### 4.2 Longitudinal variation in dent depth

In addition to the impacted part, the other sides of the damaged tube also suffer from denting damage. Therefore, an expression is necessary to specify the longitudinal variation in the dent damage. Using Eq. (8), the dent depth can be estimated at a distance $x$ from the edge of the impacted part.

$$\delta d_x = \delta_d \exp(-bx/D) \quad (8)$$

$$b = 1.4 + 3.5\exp(-15\delta_d)$$

### 4.3 Further deepening of dents due to increased bending moments

When the applied bending moment is increased, the depth of the dent can also be increased. This relationship was observed and measured in the bending tests. When performing a beam-column analysis of damaged tubes, this type of shell effect should be taken into account.

In incremental beam-column analysis, the curvature of the damaged part can be calculated using lateral deflections. Then, further deepening of the local denting damage can be estimated using Eq. (9). After obtaining this value, the shape at the locally damaged part can be reset such that the shell effect is considered in the analysis.

$$\frac{d(\delta_d)}{d\phi} = 0.0045 + 0.004\left\{\frac{\delta_d^{1.5}\sqrt{E/\sigma_Y}\exp(B/D)}{(D/t)^{0.2}}\right\}^{-0.3} \quad (9)$$

**Fig. 6** Collapsed cross-sections of damaged tubes subjected to combined axial compression and external pressure

### 4.4 Limitations of the proposed equations

When the damaged tubes are subjected to combined loadings including external pressure, the structural behavior of the locally damaged part is different from those of areas subjected to only axial compression. In Fig. 6, photographs of the cross-section of two collapsed damaged tubes which were subjected to combined axial compression and external pressure loadings are shown (Cho, 1987).

In the model with a thicker tube, (right) where $D/t$ and $\delta_d$ are 23.8 and 0.037, respectively, an apparent concave shape can be seen in the dented side but no apparent change was observed in the shape of the opposite side. On the other hand, the whole section in the model with a thinner tube with a $D/t$ and $\delta_d$ values of 41.1 and 0.183, respectively, was malformed into a peanut shell-like shape. Therefore if the equations approximating the cross section of the damaged part are used in the analysis of these tubes, the actual behavior cannot be precisely determined. A different approximation is necessary for combined loadings incorporated with external pressure.

## 5. Ultimate Bending Moment

### 5.1 Ultimate bending capacity of damaged tubulars

Most offshore tubes can be subjected to combinations of axial loads and end bending moments transmitted from adjacent members. Of course, external pressure loadings can be incorporated for members located underwater. However, that is not the dominant loading component considered in the axial compression loading analysis. Therefore, one analysis extreme is the pure axial load and the other is the pure bending moment. For combined loadings, many design equations consider the loading component interaction type. Some equations for predicting the ultimate strength of damaged tubes under pure axial compression are available in the literature (Cho, 1989). This paper provides a design equation, Eq. (10), for predicting the ultimate bending moment of damaged tubes. This equation was derived by regression analysis of the bending test results.

$$\frac{M_u}{M_p} = \exp\left[-0.04\left\{\delta_d^{0.7}(D/t) + (B/D)^{0.1}\right\}\right] \quad (10)$$

Eq. (10) considers not only the dent depth but also the width of the flattened part that comes into contact the striking object.

### 5.2 Accuracy of the design equation

The accuracy of the proposed design equation for predicting the ultimate bending moments of damaged tubes was investigated using not only the test results of this study but also those of Ueda and Rashed (1985) and Paik and Shin (1989). A comparison of the predictions using the proposed equation and those of the actual test results are summarized in Table 4.

As seen in Table 4, the mean of the actual to predicted residual strength for the 33 data points is 1.009, with a COV of 8.10%. Compared to other strength formulations, the proposed design equation provides very accurate and reliable predictions.

The comparison of the results is shown in Fig. 7, from which, it can be concluded that when a tube becomes thinner and the local denting damage increases, the residual strength of the tube can be reduced. The breadth of the denting damage also decreases the residual strength. It is also be seen in Fig. 7 that the test results reported in this paper expanded the range of the denting damage extent.

**Table 4** Comparison of ultimate bending moments of damaged tubes predicted using the proposed equation and the actual test results

| Ref. | No. of data | $(M_u)_{act.}/(M_u)_{pred.}$ Mean | COV (%) |
|---|---|---|---|
| Ueda and Rashed (1985) | 6 | 0.992 | 3.06 |
| Paik and Shin (1989) | 4 | 1.032 | 9.82 |
| This study | 23 | 1.009 | 8.80 |
| Total | 33 | 1.009 | 8.10 |

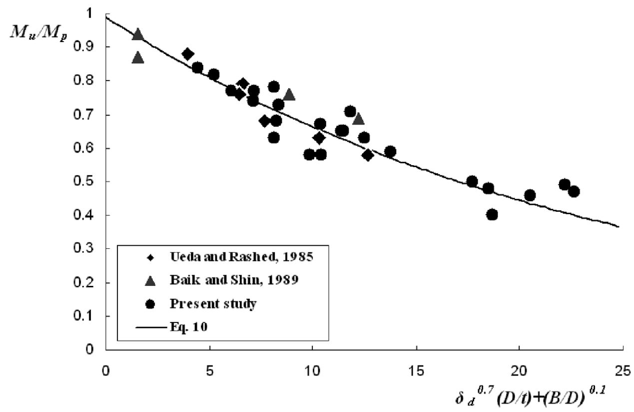



**Fig. 7** Comparison of the use of the proposed equation to predict the ultimate bending moment of damaged tubes with the use of actual test data

## 6. Conclusions

Twenty-three local denting tests and 30 pure bending tests (including seven undamaged models) were reported in this paper. The lateral denting force and denting damage relationship can be predicted with good accuracy using Eq. (1), which was derived based on the results of the denting tests.

For convenient beam-column analyses of damaged offshore tubes considering shell effects, the geometries of the damaged parts can be mathematically represented by the equations provided in this paper. In addition, the deepening of the denting damage due to increased curvature can be estimated using Eq. (9).

The residual strength of damaged tubes subjected to a pure bending moment can be predicted with good accuracy using Eq. (10). This equation can be used when developing any load component type strength formulations to predict the residual strength of damaged tubes subjected to combined axial compression and a bending moment, which is common in most offshore tubular members.

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