Ultimate strength of dented tubular members subjected to compression and bending

Y.A. Abdel-Nasser [a], K. Masaoka [b] and H. Okada [b]
[a] *Naval Architecture and Marine Eng. Dept., Alexandria University, Egypt*
[b] *Marine System Engineering Dept., Osaka Prefecture University, Japan*

The aim of this paper is to demonstrate and develop the ultimate strength analysis of tubular members with dents and subjected to combined compression and bending. The ultimate strength is calculated using a non-linear finite element system and a new simplified equation. In order to investigate a general applicability of the simplified equation, cylindrical tubes with different dented damages and subjected to combined loads are analyzed. Results of analysis demonstrate considerable accuracy of the simplified equation and good agreements with those calculated by non-linear finite element method.

الغرض من هذا البحث تحليل وتطوير المقاومة القصوى للمنشآت الأنبوبية ذات النقر تحت تأثير حمل ضغط وانحناء. وجود مثل هذه النقر سوف يؤدى الى تقليل المقاومة القصوى وكذلك طول عمر هذه المنشآت الأنبوبية. فى هذا البحث تم عرض وتحليل المقاومة القصوى لهذه المنشآت ذات النقر عند تعرضها لحمل ضغط وانحناء معا. تم اقتراح معادلة بسيطة لحساب هذه المقاومة لعدة منشآت أنبوبية ذات خواص مختلفة وقورنت النتائج بمثيلاتها بطريقة الوحدة المنتهية وكانت نتيجة المقارنة جيدة.

Keywords: Ultimate strength, Cylindrical tubes, Combined compression and bending, FEM, Dented damages

1. Introduction

Steel structures used in offshore activities are constructed from tubular members. These structures are subjected to various types of loads. Besides the normal functional loads and environmental loads, loads due to accidents may occasionally act. Among these accidental loads, collision loads due to falling objects are of special interest. The extent of damage caused by these loads ranges from total collapse of the structure to small damages which may not be serious at time of accident. Such a small damage may later affect the ability of the structure to withstand extreme loads, thus having an influence on the safety of the structure in its functional time. On the other hand, repair of such damage at sea is difficult and expensive. When a tubular member is subjected to lateral load due to collision with a vessel or a falling object the damage may take place in one of the following modes, depending on the member's geometry and intensity of the collision. These are bending of the member without denting or local denting of the member without overall bending or a combination of the two modes.

Predicting ultimate strength of tubular members is not so easy because the effect of buckling and plasticity should be considered. Studies on the influence of dented damages on the ultimate strength have been performed in many literatures. Yao et al [1] and Rashed et al. [2] suggested theoretical equations of damaged tubular member subjected to axial compression and bending. The methods are based on a yield line collapse mechanism of the dented shell. Consequently, eccentricity of the load in the dented portion of the member is accounted for. Extensive examples were compared with experimental results [3]. It is noticed that analytical equations have been in good agreement with experimental results. Ueda and Rashed [4] derived an ultimate strength interaction relationship of a dented cross section subjected to compression and bending in two perpendicular directions. Daun and Chen [5] used moment-thrust curvature relationships for predicting ultimate strength and considering the effect of local buckling on the strength of dented members. In this paper, several examples are performed on dented cylindrical tubes subjected to combined compression and bending using FEM and a new simplified equation. The presented equation depends on the yielding of the dented shell and the effect of the external acting moment. These two parameters are taken into account in the ultimate strength calculation. The procedure of the simplified equation is presented. In order to investigate the applicability of the present equation, cylindrical tubes with different geometrical properties and different sizes of dented damages are analyzed. Results of analysis are presented and compared with those analyzed by non-linear finite element method. The comparison shows good agreements.

2. Non-linear FEM method

Different numerical methods are available to analyze the behavior of structures until their ultimate strength is reached. The nonlinear Finite Element Method (FEM) is the most powerful method for analyzing complicated behavior until ultimate strength and it has a wide application in various structural fields. Using the non-linear Finite Element Method (FEM) was time-consuming in the past. However, due to improvement of computer speed and capacity, it is easy to calculate the ultimate strength in a few minutes by using FEM [6]. In this study a non-linear finite element system is applied for calculating the ultimate strength of a cylindrical tube. Four-node isoparametric shell elements are used [7]. The developed finite element system is constructed by using the principle of virtual work for each incremental step and take into account both geometrical and material nonlinearities of the shell elements. It is capable to analyze elastic-plastic behavior until and beyond the ultimate strength state. The Newton-Raphson method and the arc-length method are used to get converged solutions for each incremental step. The element can be used to accurately analyze a plate with an initial deflection and residual stresses. Different boundary and loading conditions can also be considered. Based on this system, a source code *(ULTSTRUCT*) is used in the following analyses [8].

2.1. FEM model

Figs. 1 and 2 show the FEM model of the dented tube. Fine mesh divisions are applied near the dented area along the tube length, where higher stresses are developed. While coarse mesh divisions are applied far away from the dented area. Rigid elements are assumed at both ends of the tube to prevent local failures near tube ends where external loads are acting.

2.2. Comparison between FEM and experimental results

Several examples are performed using non-linear finite element method for cylindrical tube with dents at various locations of its length. Among those, two cases are presented. First case is a simply supported tube with a dented damage at its quarter length and subjected to combined compression and bending. Second case is a fixed tube at both ends and with a dented damage at its middle length and subjected to compression. The geometrical properties, loading and boundary conditions are shown in table 1.

Fig. 3-a shows the relationship between the normalized load (P/P_o) and deflection-length ratio (w/L) for the first case. while fig. 3-b shows results for the second case. In these figures, the solid line refers to results using FEM and the dotted line to those by experimental work [1]. It is shown that the FEM simulates the behavior of the dented tubes similar to that by the experimental work.

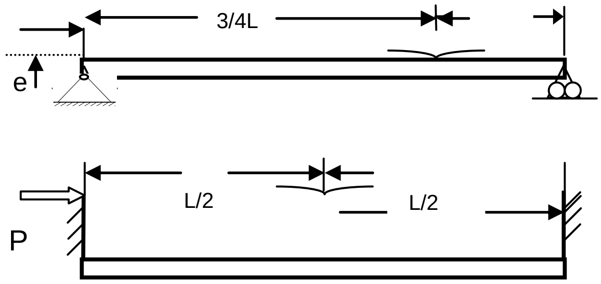
Fig. 4 shows the ultimate strength calculation for other cases of dented tubes simply supported at their ends. The results are compared with other measured ones. Small difference between results may be observed.

3. Prediction of ultimate strength using analytical equations

Different analytical approaches for predicting the ultimate strength of dented tube subjected to combined loads are presented. Sherif et al. and Yao etal have developed analytical equations based on a yield line collapse mechanism of the dented shell for calculating the ultimate strength. Extensive examples were compared with experimental results [1,2]. The methods showed consider

Table 1
Loading and boundary conditions of dented tubes

Conditions / Properties	-Simple S. -dent at ¾ L	-Fixed S. -dent at ½ L
L, length, mm	2500	3500
D, diameter, mm	122.04	123.21
d depth of dent, mm	11.58	6.17
σ_o yield strength N/mm^2	520	213
E modulus of elasticity N/mm^2	207000	207000
t, thickness, mm	3.04	2.1
w_0 initial deflection, mm	4.12	2.58
e eccentricity, mm	6.0	0.0
λ slenderness ration	0.95	0.84
D/t	40.14	58.67



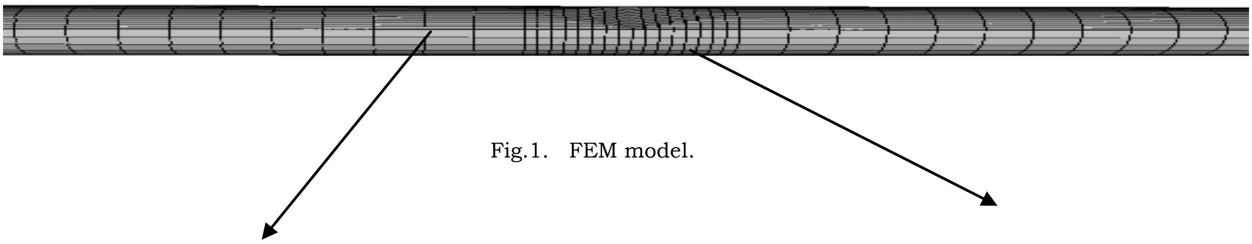


Fig. 1. FEM model.

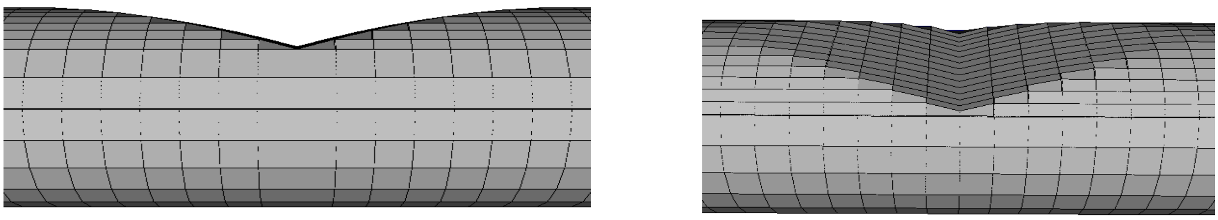


Fig. 2. Dent size and its location.

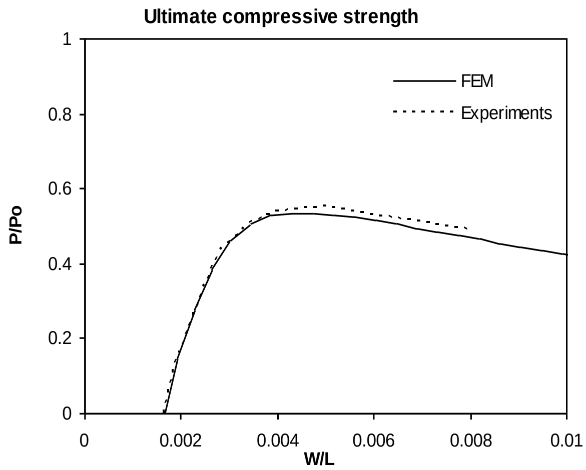


Fig. 3-a. P/P_o -w/L relationship.

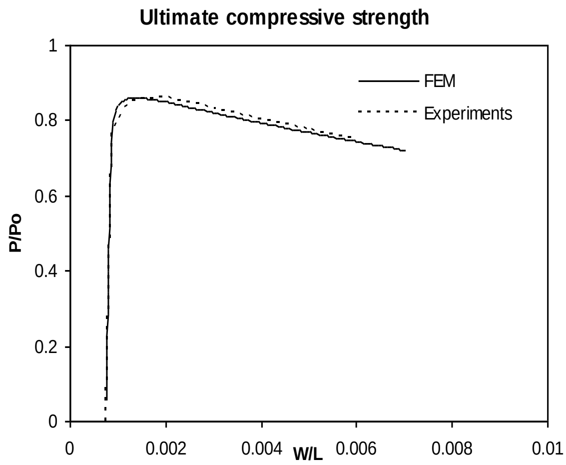


Fig. 3-b. P/P_o -w/L relationship.

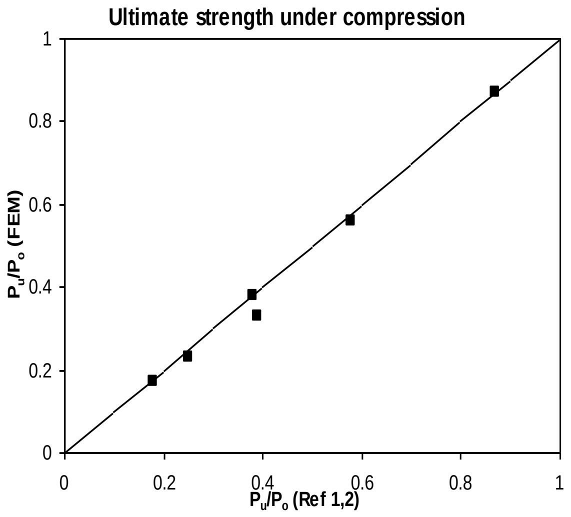


Fig. 4-a. Ultimate strength under compressive load.

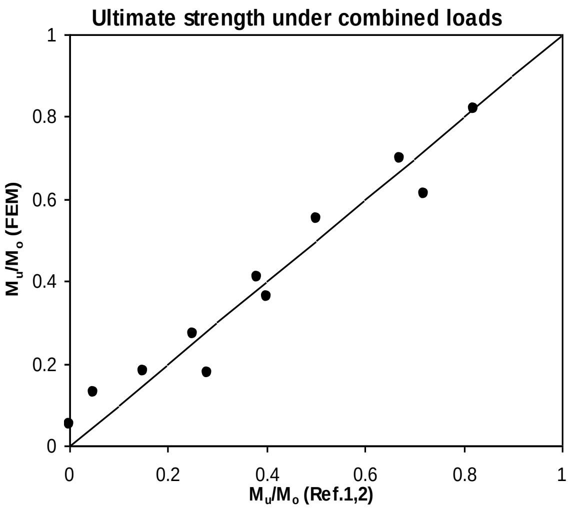


Fig. 4-b Ultimate strength under combined loads.

able agreement with measurements by experimental work for tubular members. In this study, for other tubes with higher slenderness ratio, a difference is observed between results of FEM and analytical ones. A modification is suggested in the analytical equation taking into account the yielding of the dented shell and a magnification factor due to the external acting moment. The present equation is presented as follows:

1. Yielding of the dent region: Yielding starts at the flattened part of the dent area where maximum stresses are developed due to compression and bending as shown in fig.5. Yielding continues until a full plastic hinge line is formed. Integrating the full plastic stresses at the middle of dent area, the acting stress σ_{dp} is expressed as [2],

$$\sigma_{dp} = \sigma_o \sqrt{4(\mu/t)^2 + 1} - 2\mu/t, \quad (1)$$

where,

μ is the centre of the arc at the location of dent as shown in fig. 5. $D(\sin\alpha/\alpha - \cos\alpha)/2$, and

α is the $\cos^{-1}(1\text{-}d/D)$.

At this stage the acting compressive load on the tube is,

$$P_{dp} = \sigma_{dp} A'. \quad (2)$$

2. The ultimate strength stage: After plastification has occurred at the dent region, eccentricity due to an additional acting load P_2 starts which develops overall moment acting on the tube. The lateral deflection is substantionally increased and yielding at the adjacent region to the dent area starts and tube stiffness decreases rapidly. When the acting load P_2 reaches its maximum value, the ultimate strength is attained. The ultimate strength stage may be discussed as follows,

Assuming the tube has an initial deflection function expressed by a Fourier series as follows,

$$w_o(x) = \sum_{i=1}^{2} w_{oi} \sin(i\pi x/L), \quad (3)$$

where,

e_p is the shift in the natural axis $= D \sin\alpha/(\pi - \alpha)$,

w_{oi} is the $(e_p + w_o)A_i$, and

A_i is the a coefficent given in ref. [9].

Substituting w_o in the following governing equation, we get,

$$EI\delta^4(w - w_o)/\delta x^4 + P_2\, \delta^2 w/\delta x^2 = 0. \quad (4)$$

The developing moment M_i due to addtional load P_2 is expressed by eq. (5) as follows [9],

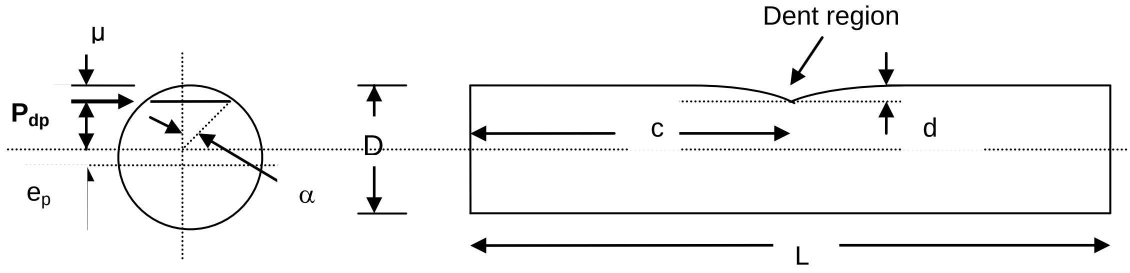


Fig. 5. Section through the middle of the dent.

$$M_i = P_2 w = P_2 \sum_{i=1}^{2} w_{oi} \, \sin(i\pi c/L)/\{1-(1/i^2)(P_u/P_e)\}, \quad (5)$$

where,

P_2 is the $P_u - P_{dp}$,

P_u is the ultimate compressive load, and

P_e is the Euler buckling load$=E\pi^2 I/L^2$.

The maximum moment ocurrs when the coefficent w_{oi} of eq. (5) is maximum [10]. It is assumed that the maximum deflection at $x=L/2$, ($A_1=1$, $A_2=0$).

Hence, M_i may be expressed as follows.

$$M_i = P_2\,\delta_2 + P_{dp}\,\delta_1, \quad (6)$$

where,

$\delta_2 = (e_p+w_o)\,\phi$, $\delta_1 = w_o\,\phi$,

$\phi = 1/(1-p_u/p_e)$.

When the dented tube is subjected to combined compression load P_u and bending moment M_u, then the maximum moment may be expressed as follows;

$$M_{max} = M_u/\cos\{(\pi/2)\sqrt{(P_u / P_e)}\} + P_2\,(e_p+w_o)\,\phi + P_{dp}\,w_o\,\phi . \quad (7)$$

The above equation is approximated as follows,

$$M_{max} = \{M_u + P_2\,(w_{o}+e_p) + P_{dp}\,w_o\}\,\phi . \quad (8)$$

3. The stress distribution acting on the tube at the dent region is as shown in fig. 6, the interaction equation of the ultimate strength of the dented tube subjected to combined compression load P_u and bending moment M_u is expressed as:

$$M = M_p\{(2\sigma_{dp}/\sigma_o)\sin\alpha + \sin(\tfrac{1}{2}\pi[P_1-P_u]/P_p) - \tfrac{1}{2}\sin\alpha\}. \quad (9)$$

From eqs. (8) and (9), M_u is expressed as follows:

$$M_u = M_p\{(2\sigma_{dp}/\sigma_o)\sin\alpha + \sin(\tfrac{1}{2}\pi[P_1-P_u]/P_p) - \tfrac{1}{2}\sin\alpha\}/\phi - P_2\,(w_{o}+e_p) + P_{dp}\,w_o , \quad (10)$$

where,

$P_1 = \sigma_o Dt(\pi-\alpha) + \sigma_{dp} Dt\alpha.$

$M_p = \sigma_o D^2 t$, $P_p = \sigma_o \pi Dt.$

4. Finally, for dented tubes subjected to only compression, the ultimate compressive load is given as follows,

$$P_u = (\sigma_o - \sigma_{dp} - P_{dp}\,\delta_1/Z')/(1/A' + \delta_2/Z'). \quad (11)$$

Where,

$A' = (\pi-\alpha)Dt$, $A = \pi Dt$

$Z' = 2I'/D$

$$I = (\pi/8)D^3 t - Dt\alpha\,(\tfrac{1}{2}D\sin\alpha/\alpha + e_p\}^2 + 2Ae_p^2. \quad (12)$$

Damage -3 (d/D=0.2)	λ =0.75	λ =1.0	λ =1.5	λ =2.0
Geometrical properties	L =2500 D/t =50 σ_o =360	L =3400 D/t =50 σ =360	L =5000 D/t =50 σ_o =360	L =6600 D/t =50 σ_o =360
Damage-4 (d/D=0.1)	λ =1.0	λ =1.0	λ =1.0	
Geometrical properties	L =3400 D/t =25 σ_o =360	L =3400 D/t =50 σ_o =360	L =3400 D/t =85 σ_o =360	

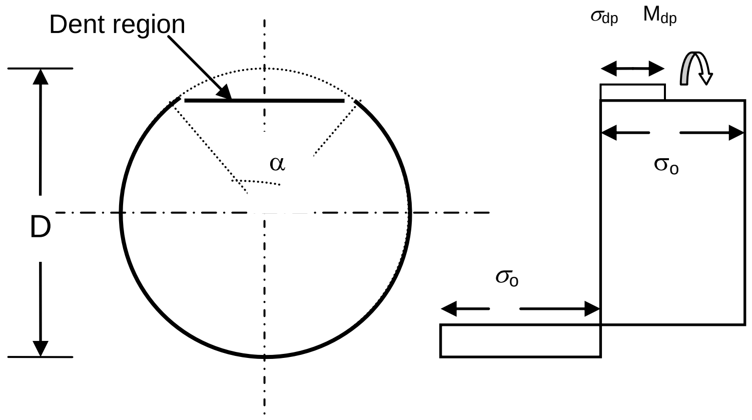


Fig. 6. Stress distribution at the ultimate stage through cross section.

4. Examples of numerical analyses

4.1. Geometrical properties and loading conditions

Several models of cylindrical tubes with different geometrical properties are analyzed. Different sizes of dented damages ratio such as d/D=0.05, 0.1 and 0.2 in the middle of the tube length and slenderness ratio λ =1 and 2 are considered. Amplitude of initial deflection of value equal L/1000 is assumed. Different ratios of D/t equal 25, 50 and 85 are also investigated. The cylindrical tube is assumed to be simply supported at both ends and subjected to combined compression and bending as shown in fig. 7. The geometrical properties and loading combination factors are shown in tables 2 and 3.

where,

λ is the $(L/\pi r)\,(\sigma_o/E)^{.5}$,

r is the $(I/A)^{.5}$,

σ_o is the yield strength, N/mm^2

w_o is the initial deflection =L/1000, mm, and

F is the maximum acting load, N.

4.2. Parametric study

Applying eq. (10), the interaction curve of ultimate strength for dented tubes subjected to combined compression and bending could be calculated. Then, results of analyses are compared with those analyzed by FEM and other analytical methods. Figs. 8 to 13 show relationships between the ultimate load (P_u/P_o) and ultimate moment (M_u/M_o) for cases of d/D =0.05, 0.1 and 0.2 as described in table 2. The most important effect on the deterioration of the ultimate strength is the size of the dent and the tube slenderness ratio. It is observed from these figures that both compressive and bending ultimate strengths remarkably decrease as the size of dent increases and the deterioration in the ultimate strengths is increased as the slenderness ratio increases. t is seen that the results based on the present equation have considerable agreement with

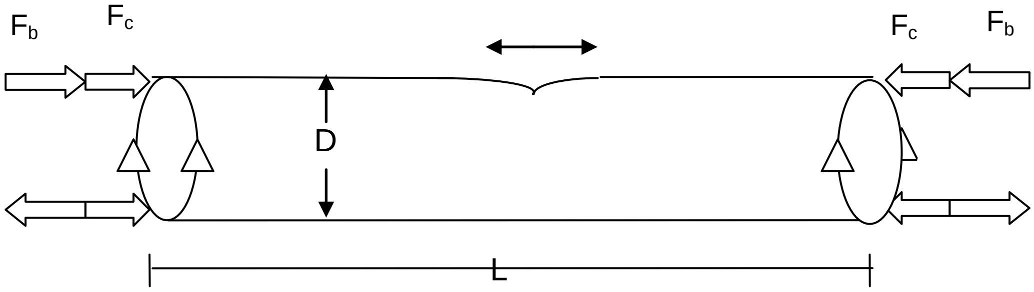


Fig.7. E conditions.

Table 2
Geometrical properties of the models

Damage -1(d/D=0.05)	λ =0.75	λ =1.0	λ =1.5	λ =2.0
Geometrical properties	L =2500 D/t =50 σ_o =360	L =3400 D/t =50 σ_o =360	L =5000 D/t =50 σ_o =360	L =6600 D/t =50 σ_o =360
Damage -2 (d/D=0.1)	λ =0.75	λ =1.0	λ =1.5	λ =2.0
Geometrical properties	L =2500 D/t =50 σ_o =360	L =3400 D/t =50 σ_o =360	L =5000 D/t =50 σ_o =360	L =6600 D/t =50 σ_o =360

Table 3
Combination load factors

Combination load factors	$C1$	$C2$	$C3$	$C4$	$C5$
Compression force , F_c	0.025F	0.25F	0.50F	0.75F	1.0F
Bending force, F_b	0.975F	0.75F	0.50F	0.25F	0

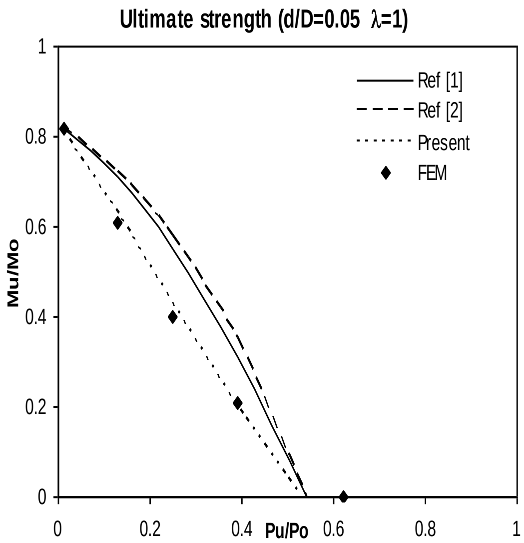


Fig. 8. Ultimate strength interaction curves.

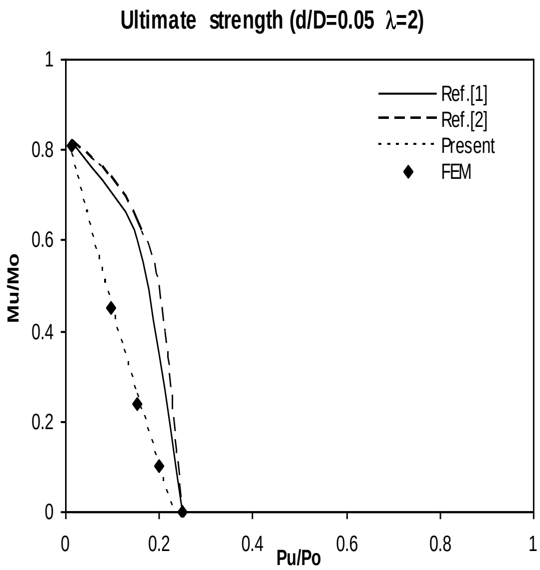


Fig. 9. Ultimate strength interaction curves.

those by FEM for most cases of dented tubes. A difference between FEM results and those applied in refs. [1] and [2] have also been observed for cases of tubes having higher slenderness ratios.

When a compressive load is acting alone on tubes having lower slenderness ratio, FEM results show higher estimation than those by analytical ones. While for tubes with higher slenderness ratio, FEM predicts lower estimation of the ultimate strength as shown in figs. 11 and 13.

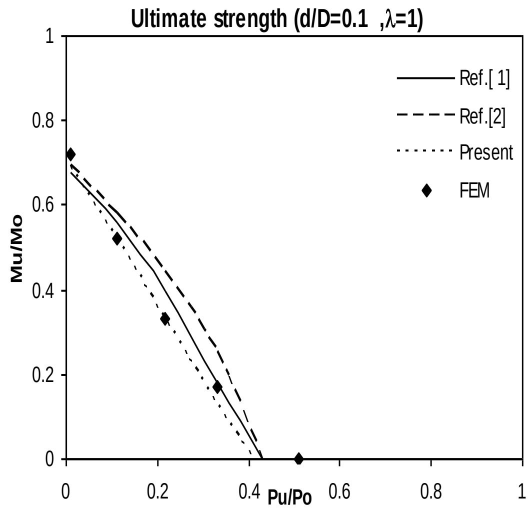


Fig.10. Ultimate strength interaction curves.

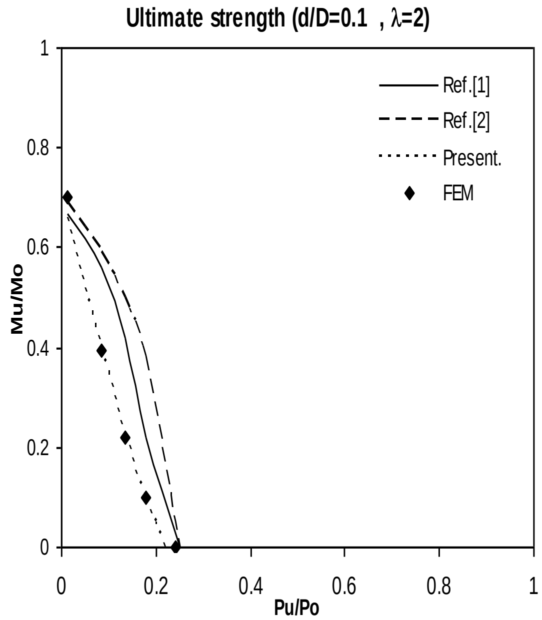


Fig.11. Ultimate strength interaction curves.

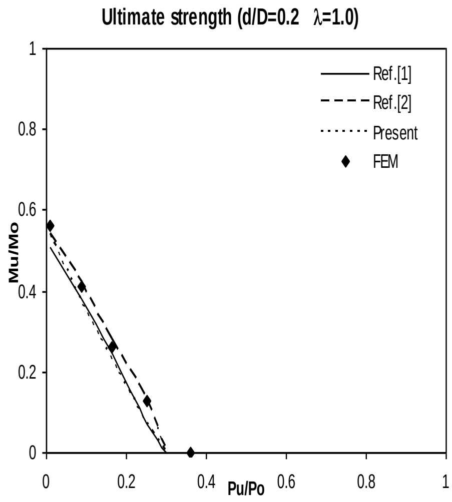


Fig. 12. Ultimate strength curves.

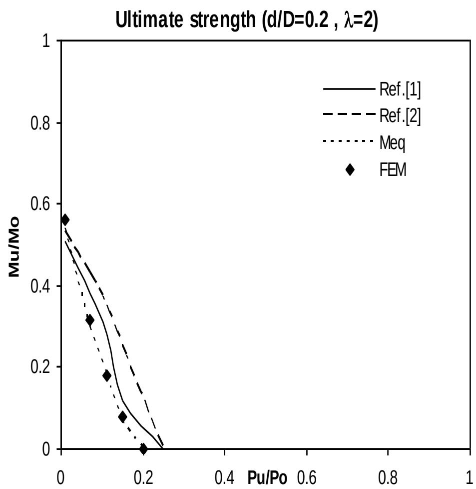


Fig.13. Ultimate strength interaction curves.

Fig. 14 shows relationships between the ultimate load (P_u/P_o) and ultimate moment (M_u/M_o) for cases of d/D=0.1 and D/t =25, 50 and 85. It is shown that the results of analyses by the present equation have considerable agreement with those by using FEM. Fig. 15 shows same relationships for tubes with different sizes of dents. The results are also compared with FEM results.

Figs. 16 and 17 show ultimate strength interaction curves for cylindrical tubes with different slenderness ratio for cases of damages such as d/D=0.1 and d/D=0.2

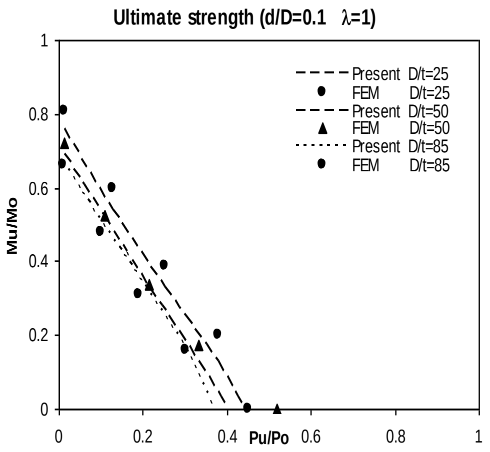


Fig.14. Ultimate strength curves.

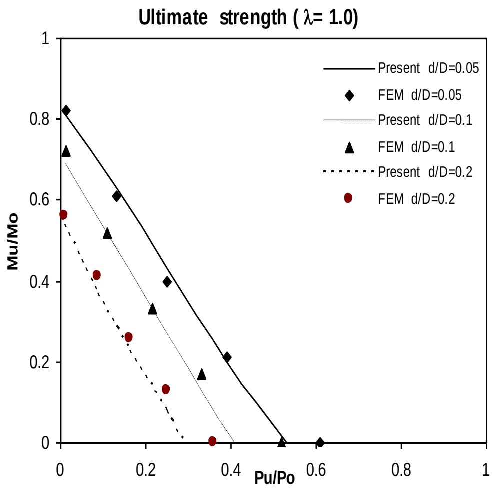


Fig.15. Ultimate strength interaction curves.

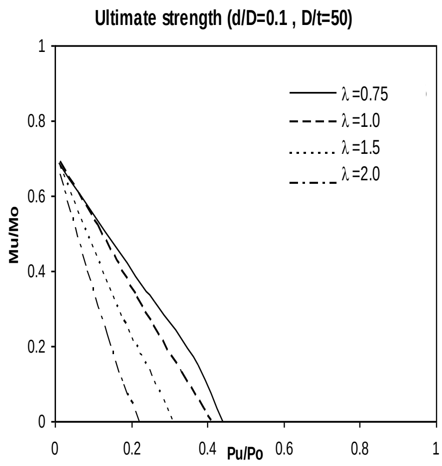


Fig.16. Ultimate strength interaction curves.

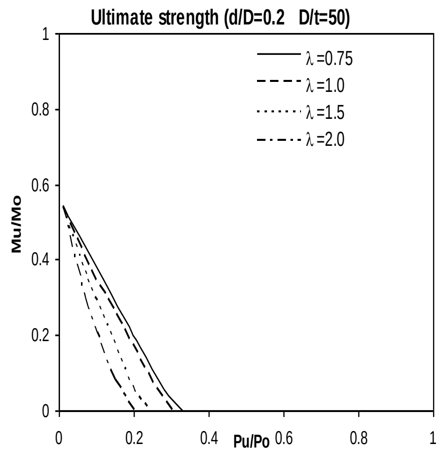


Fig.17. Ultimate strength interaction curves.

5. Conclusions

This paper has demonstrated the degradation of the ultimate strength of dented cylindrical tubes and subjected to combined compression and bending moment. A simplified interaction equation is proposed to calculate the ultimate strength of dented tubes. The results of analyses based on both the simplified equation and non-linear finite element system are presented. From these results, the following conclusions may be concluded:

1. FEM code (*ULTSTRUCT*) simulates behavior stages of dented tubes similar to that by experimental work.
2. The results calculated by the present method are confirmed with those by using non-linear finite element system for various D/t and slenderness ratios.
3. Some differences are observed in the results for cases of dented tubes having lower slenderness ratio and subjected to only acting compressive force.

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