

DENTING AND COLLAPSE OF THIN-WALLED RISERS UNDER LATERAL LOADS

Claudio Ruggieri
Dept. of Naval Architecture and Ocean Engineering,
University of São Paulo
São Paulo, SP 05508–900, Brazil
Email: claudio.ruggieri@poli.usp.br

José Alfredo Ferrari Jr.
Petróleo Brasileiro S. A. - Petrobrás,
Exploitation and Production (E&P) Division
Rio de Janeiro, RJ 20035-900, Brazil
Email: jaferrari@petrobras.com.br

Abstract: Structural behavior of dent damaged tubular members by local indentation remains a key issue for the safety and failure assessment of critical structures, including marine and nuclear facilities, and oil and gas pipelines. This failure mode most often arises from very large localized plastic deformations caused mainly by excessive or accidental loads such as, for example, during the collision of adjacent risers in deepwater floating production systems (FPS), during the excavation of buried pipelines or pipe–on–pipe impact events in nuclear power plants. The complex interaction between the local deformation in the dented region and global bending of the tubular member may severely reduce the plastic collapse load while, at the same time, strongly affecting its load–deflection behavior. A numerical investigation of the structural behavior of a dented tubular member under lateral loads is the focus of this study. 3D finite element models are employed to generate numerical solutions describing the large deformation, non–linear behavior of a steel pipe with varying restraint conditions (simply supported and fixed ends) and subjected to local indentation by lateral loading. Experimental load–deflection curves measured using a 114.5 mm API N80 pipe (yield stress = 640 Mpa) agree well with the numerical results. The analyses enable the development of improved design criteria to tubular members and risers which consider dent damage effects.

Keywords: *riser collision, dent damage, structural integrity, finite elements*

1. Introduction

Structural integrity assessments of damaged marine risers by local indentation remain a key issue in design and safety analysis procedures of deep-sea floating oil and gas production systems. Dent damage in structural tubular members and marine risers most often arises from very large localized plastic deformation caused primarily by impact loads. For close arrays of top-tensioned risers (TTR), the dynamic behavior mismatch of adjacent risers (associated, for example, with partial loss of riser tension) causes different dynamic response of these structures [1,2]. During service, platform motion and hydrodynamic loads subject the risers to large relative displacements which can potentially cause collision of the adjacent risers and create dented regions in any location and orientation along the outer shell of the colliding tubular structures as illustrated in Fig. 1. The complex interaction between the local deformation in the dented region and global bending of the riser may severely reduce the plastic collapse load while, at the same time, strongly affecting its load-deflection behavior.

Methodologies to analyze the damage of tubular structural components subjected to impact loading have evolved primarily along assessing their residual strength. Examples of such methodologies include damage assessment guidelines for offshore structures adopted by API RP 2A [3] which build on earlier work of Ellinas and Walker [4]. These guidelines provide limiting values for dent depth in bracing members following ship collision or accidental loads which were mainly derived from the observed behavior of plastic beams under lateral loads. For simply supported, thin-walled tubes with diameter D and thickness t, the development of local denting at the load point followed by global bending significantly reduces the nominal plastic limit load due to reduced plastic modulus section [5-10]. Consequently, predictions of structural failure in damaged tubular members require accurate relationships between the impact load and dent depth.

This study presents an experimental and numerical investigation of the structural behavior of a dented tubular member under lateral load which is applicable to marine risers. Experimental load-deflection curves measured using a 4 1⁄2” O.D. (114 mm) API N80 pipe (580 MPa yield stress) with varying length characterize the plastic response during local indentation and global bending. 3D finite element models are employed to generate numerical solutions describing the large deformation, non-linear behavior for the tested pipes. The experimental results agree well with the numerical results. The article also examines the effects of dent damage on the load-carrying capacity of a typical production riser by conducting a parametric

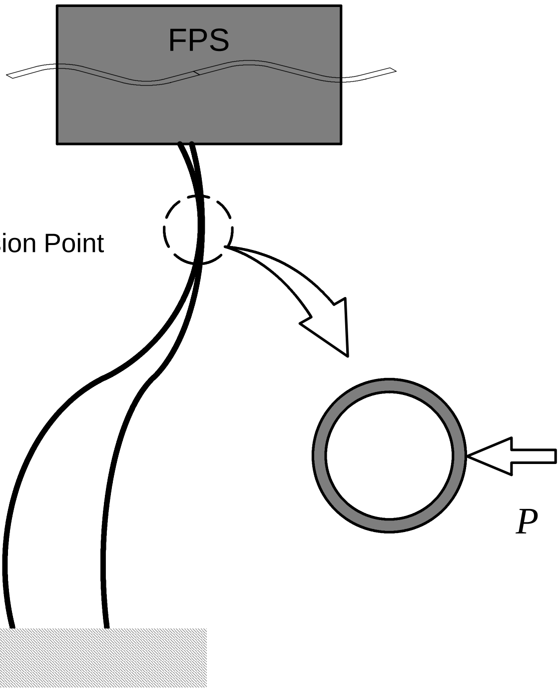

Figure 1 *Schematic illustration of potential collision between two adjacent risers.*

analyses on steel tubes ($D = 9\,5/8$" (245 mm)) with varying length and diameter to thickness (D/t) ratio. The analyses provide further insight into the structural response of tubular members and risers with dent damage effects.

2. Experimental Test Program

2.1. Denting and Bending of Simply Supported Pipe Specimens

Dent and bend tests were performed on 4 1⁄2" O.D. (114 mm) pipe specimens with 7 mm wall thickness. Figure 2(a) shows a schematic illustration of the test rig employed for loading the simply supported tubes. The experimental program included pipe specimens with different load spans (S) defined as the length between supports (see Fig. 2): $S = 1000$, 2000 and 3000 mm. The pipe specimens were supported on two rollers to ensure that no significant end constraints could develop. The axes of these rollers were bolted to a rigid fixture which was placed on the base plate of the testing machine. The load was applied to the center of the pipe using a rigid tube-shaped indenter with the same diameter as the pipe specimen to simulate the riser-to-riser collision.

A special rig was also designed and built to simulate the axial tension loading usually applied to marine risers. Figure 2(b) shows a schematic illustration of the test rig employed which allows axial displacement and free rotation at the support points. For this constraint condition, the experimental program included pipe specimens with $S = 1000$ and 3000 mm subjected to different levels of axial tension, $T = 0$ (no axial tension), 12 and 24 tf. The axial force $T = 24$ tf corresponds to the top tension which would be applied to a marine riser of 4 1⁄2" O.D. and 1000 m length to provide an overbalance (positive tension) of $\sim 35\%$ its total weight. The axial load was applied by a hydraulic transverse jack and a load cell bolted to a rigid, horizontally free plate. The span S^* between the supports and the axial load bolt is 720 mm. The axial load was held constant throughout the test while the lateral load was applied incrementally. Similarly to the simply supported pipe tests, the lateral load was also applied to the center of the pipe span S using a rigid tube-shaped indenter with the same diameter as the pipe specimen to simulate the riser-to-riser collision

2.2. Mechanical Properties of Tested Steel

Mechanical tensile tests conducted on standard tensile specimens (ASTM E8M) provide the room temperature (20_C) stress-strain data. The material is a high strength pipe steel API 5CT N80 with yield stress $\sigma_{ys} = 580$ MPa and a relatively high hardening behavior ($\sigma_{ys}/\sigma_t = 0.69$). Other mechanical properties for the material include Young's modulus, $E = 200$ GPa and Poisson's ratio, $\nu = 0.3$. Ruggieri and Ferrari [13] provide the engineering stress-strain data for the tested steel.

2.3. Experimental Results

Figures 3(a) shows the indenter load (P) *vs.* dent depth (δ) curves for the simply supported tested pipes. The load is applied in increments of 1000 kgf in the linear and quasi-linear region of the curves ($\delta \approx 1 \sim 3$ mm). Before of the attainment of the

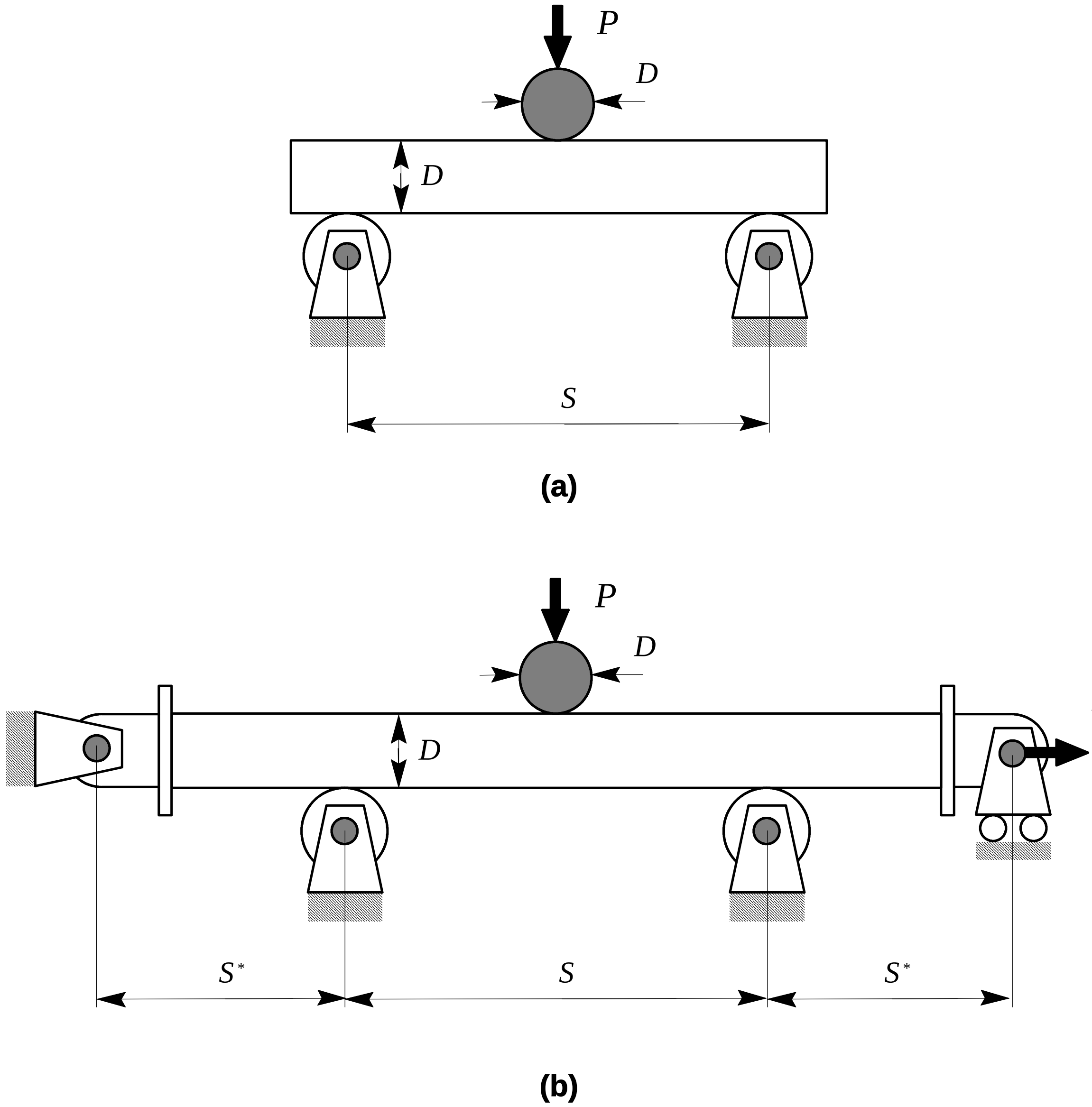

Figure 2 *Schematic illustration of test rig for testing the pipe specimens with a rigid cylindrical indenter having the same diameter as the tube: (a) simply supported pipes; (b) axially loaded pipes.*

(anticipated) maximum load, the load increment is reduced to 500 Kgf. After each increment, the load was removed and the dent depth was measured.

For all pipe specimens, the load rises steeply for small values of dent depth which marks the *pure* denting process. With the interaction of local denting and global bending, the dent depth increases at a larger rate (with the dent force increasing slowly) until the limit-collapse load is reached. Here, the strong bend fields that develop for larger values of dent depth ($\delta \gtrsim 5 \sim 10$ mm) causes large deflections accompanied by large plastic rotations thereby leading to beam instability. As it might be anticipated, the maximum load is strongly dependent of load span (S); here, the maximum load obtained in the tests increases for decreased values of S.

The effect of local denting is to reduce the pipe section modulus while, at the same time, causing load eccentricity within the damaged area as the beam deflection is increased. Figure 4 shows the damaged area for the pipe specimen with $S = 1000$ mm at the maximum load reached in the tests. As already noted, the growth of the dented region produces a significant reduction of the pipe modulus section which strongly affects its load-carrying capacity. Furthermore, such large plastic region clearly indicates the large energy-dissipation capability of the steel pipe during the performance of plastic work by the lateral load. Such features are central to the design and safety assessment procedures of colliding marine structures.

Figure 3(b) shows the indenter load (P) *vs.* dent depth (d) curves for the axially loaded pipe specimens with different load span, $S = 1000$ and 3000 mm, and different applied axial forces, $T = 0$ (no axial tension), 12 and 24 tf. The pipe specimen with $T = 0$ and $S = 1000$ mm enables comparisons of the effect of the pipe end constraints (simply supported *vs.* horizontally free) on the structural response. The experimental results clearly show increased levels of lateral load with dent depth for

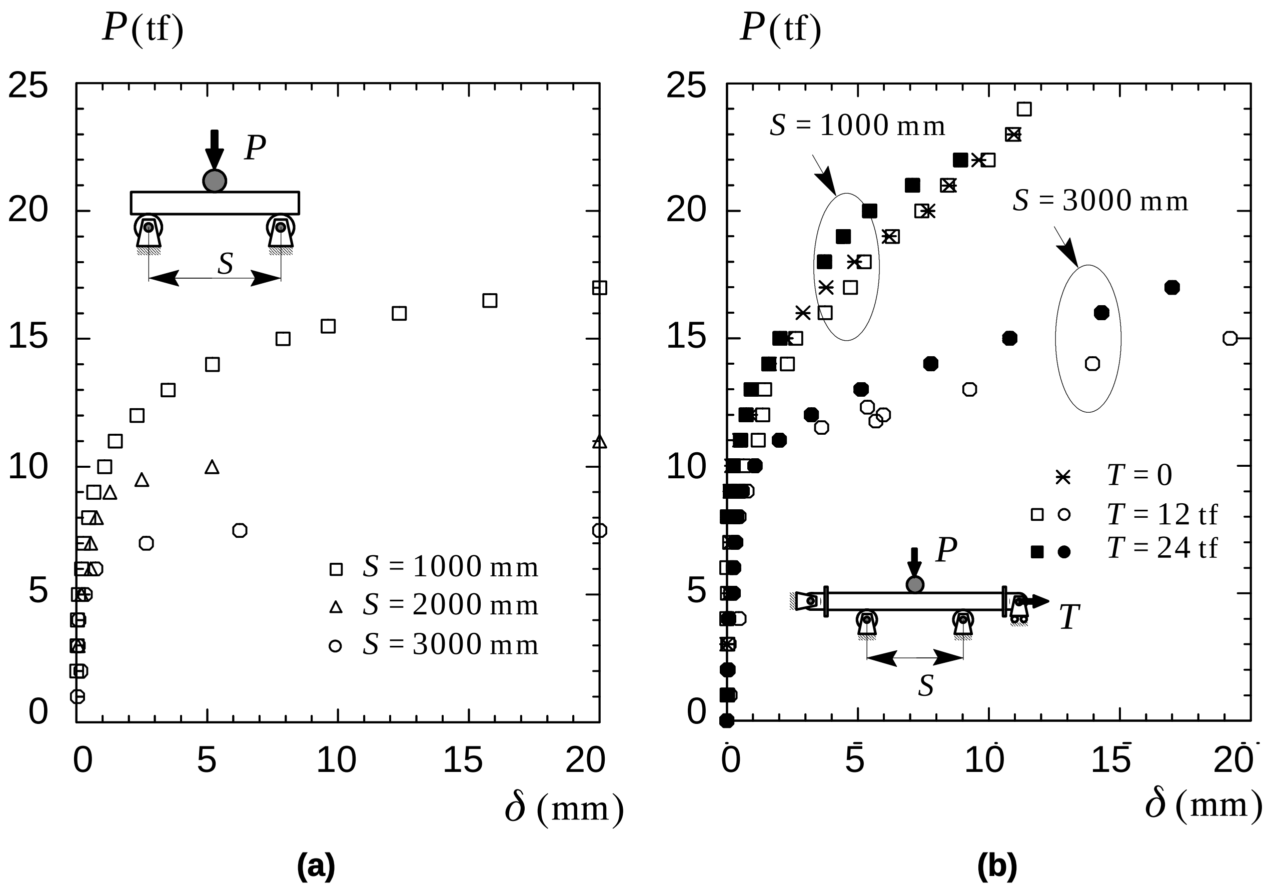

Figure 3 *Measured indenter load vs. dent depth: (a) simply supported tested pipes; (b) axially loaded pipes.*

the horizontally free pipe specimen. Because the pipe end constraints generate additional restraint to large deflections and large plastic rotations, the load-carrying capacity for the tubular beam is increased with respect to the simply supported pipes. However, the most striking result that emerges from the plots shown in Fig. 3(b) is the weak dependence of the P-δ curves on the applied axial force, T. For small values of dent depth ($\delta \approx 1 \sim 3$ mm), the structural response is essentially similar for all pipe specimens. For larger values of dent depth, the pipe specimens with $S = 1000$ mm continue to display the same trend, whereas there is a relatively larger effect of T on the P-δ curves for the pipe specimens with $S = 3000$ mm. While the axial tension (and associated end constraints imposed by the test rig employed) increases the *global* bending stiffness, it has only little influence on the *local* stiffness associated with the plastically deformed zone at the dented region. The numerical analyses for a 9 5/8" O.D. production riser shown in Section 5 also reveal similar trends in that the axial tension does not alter significantly the structural behavior of tubular beams under lateral loads.

3. Computational Models

3.1. Solution Procedures

The three-dimensional computations reported here are generated using the research code WARP3D [11] which: (1) implements a Mises constitutive model in a finite-strain framework, (2) solves the equilibrium equations at each iteration using a linear pre-conditioned conjugate gradient (LPCG) method implemented within an element-by-element (EBE) software architecture, (3) implements a frictionless, rigid-body contact algorithm using a standard penalty method, (4) analyzes numerical models constructed with three-dimensional, 8-node tri-linear hexahedral elements. Use of the so-called $\overline{\boldsymbol{B}}$ formulation [12] precludes mesh lock-ups that arise as the deformation progresses into fully plastic, incompressible modes. The LPCG approach reduces memory sizes and execution times significantly below those for sparse direct solvers (no assembly of the system stiffness matrix).

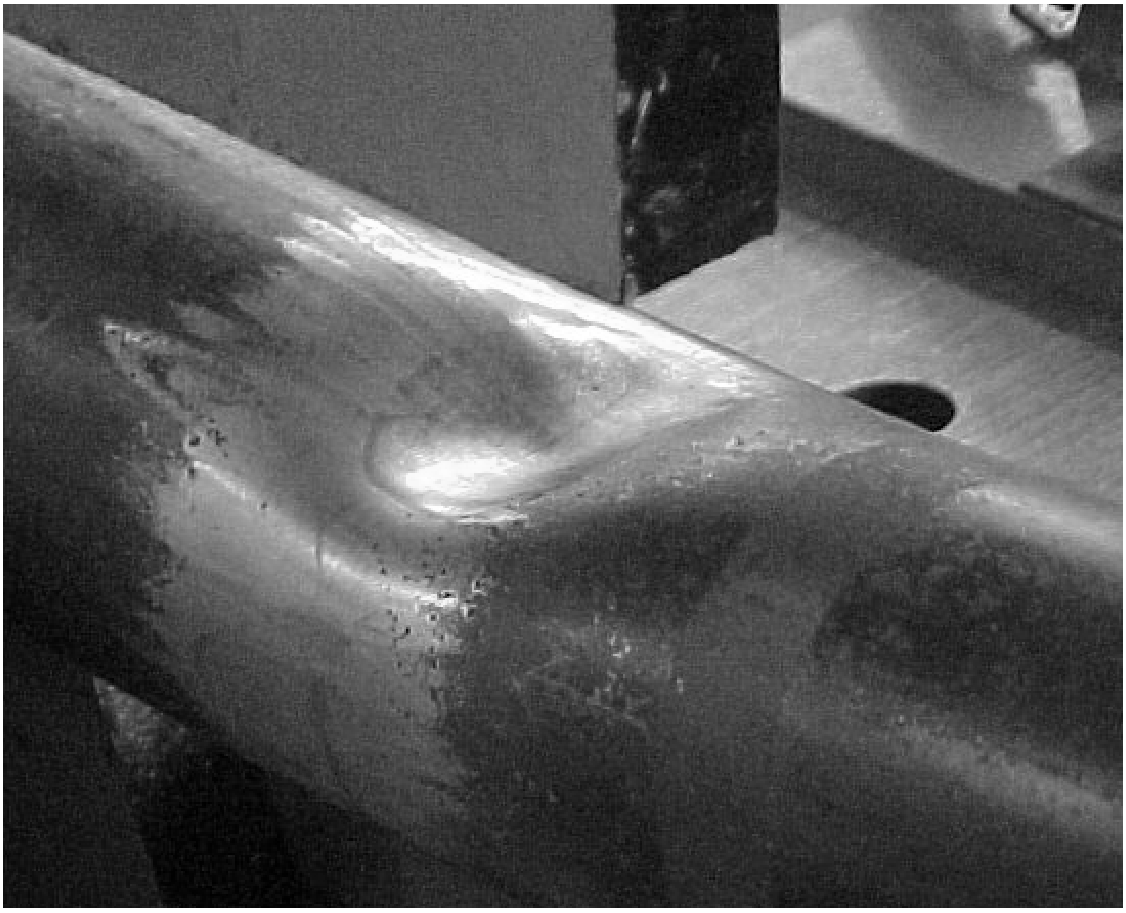

Figure 4 *Growth of dented region for the simply supported tested pipe with S = 1000 mm at maximum load.*

The numerical simulation of the indentation process involves the contact interaction between the pipe specimen and the rigid cylindrical indenter (see Fig. 2). WARP3D uses a simple penalty method to enforce displacement constraints in the solution of the finite element model which creates springs at the contact points. The spring stiffness corresponds to the penalty parameter, while the amount of remaining penetration corresponds to the error in the enforcement of the constraint. WARP3D adds each spring stiffness into the corresponding element stiffness matrices instead of directly into the global stiffness matrix. This approach allows full use of the element-by-element architecture inherent inside WARP3D, as well as the linear preconditioned conjugate gradient solver (LPCG). Contact between two deformable bodies requires application of the contact force to the penetrating node and the penetrated element. However, rigid body contact eliminates the need to compute forces on penetrated elements; the contact springs only affect penetrating nodes. This greatly simplifies the calculation of contact forces and the additions to element stiffness matrices [11].

The elastic-plastic constitutive model employed in the analyses follows a J_2 flow theory with conventional Mises plasticity. A piecewise linear approximation to the measured tensile response for the material provided by Ruggieri and Ferrari [13] is adopted to generate numerical solutions for the pipe specimens described next.

Additional analyses are also conducted to evaluate dent damage effects for a 9 5/8" production steel riser. Here, the elastic-plastic material stress-strain response follows a simple power-hardening model given by

$$\frac{\epsilon}{\epsilon_0} = \frac{\overline{\sigma}}{\sigma_0} \quad \epsilon \leq \epsilon_0 \ ; \quad \frac{\epsilon}{\epsilon_0} = \left(\frac{\overline{\sigma}}{\sigma_0}\right)^n \quad \epsilon > \epsilon_0 \tag{1}$$

where σ_0 and ϵ_0 are the reference (yield) stress and strain, and n is the strain hardening exponent. These finite element analyses consider material flow properties covering a typical structural steel applicable in marine risers (*e.g.,* API X60): $n = 10$ and $E/\sigma_0 = 500$ with $E = 206$ GPa and $\nu = 0.3$.

3.2. *Finite Element Models*

Figure 5 shows the finite element model constructed for 3-D analyses of the pipe specimen with $S = 1000$ mm utilized to measure the load-dent depth response for the structural steel employed in this study. The 3-D model has 11200, 8-node elements and 14555 nodes. The elements are arranged into variable thickness layers over the half-span ($S/2$). Very similar finite element models and mesh configurations are employed for other pipe configurations ($S = 2000$ and 3000 mm). The geometry and size of the models match those for the specimens tested in the experiments previously described (see Fig. 2). Symmetry of the geometry and loading conditions enable analyses using only one-quarter, 3-D model of the specimens. Appropriate constraints are imposed on the symmetry planes. Displacement controlled loading of the models as indicated in Fig. 5 permits continuation of the analyses once the load decreases for increased values of dent depth.

The finite element model for the $9\,5/8$" production riser has very similar mesh details. The analyses employ numerical models with varying load spans ($S = 1000$, 2000, 3000 and 6000 mm) and varying diameter to thickness (D/t) ratios: $D/t = 10$, 15 and 20. A typical 3-D model ($S = 3000$ mm and $D/t = 20$) has 5200, 8-node elements and 6900 nodes. Symmetry and loading conditions follow those already shown in Fig. 5

4. Numerical Response of Tested Pipes

4.1. *Structural Behavior of Tested Pipe Specimens*

This section presents the results of detailed numerical simulations of the load-dent depth response for the tested pipe specimens. Figure 6(a) compares the numerical predictions with the experimental results for the simply supported tested pipes ($S = 1000$, 2000 and 3000 mm). The analyses capture the essential features of the structural behavior for the dented pipes. In particular, the prediction of structural collapse (instability load at which large dent growth is accompanied by large plastic rotations) for the pipe specimens agree very well with experiments. The initial phase of the denting process ($\delta \approx 1 \sim 2$ mm) is somewhat underpredicted by the numerical analyses. This may be due to larger errors in the experimental measurement of pipe damage for small values of dent depth. As previously mentioned, the test load is removed before measuring the denting which causes elastic unloading of specimens; such effect is not accounted for in the numerical analyses. However, as

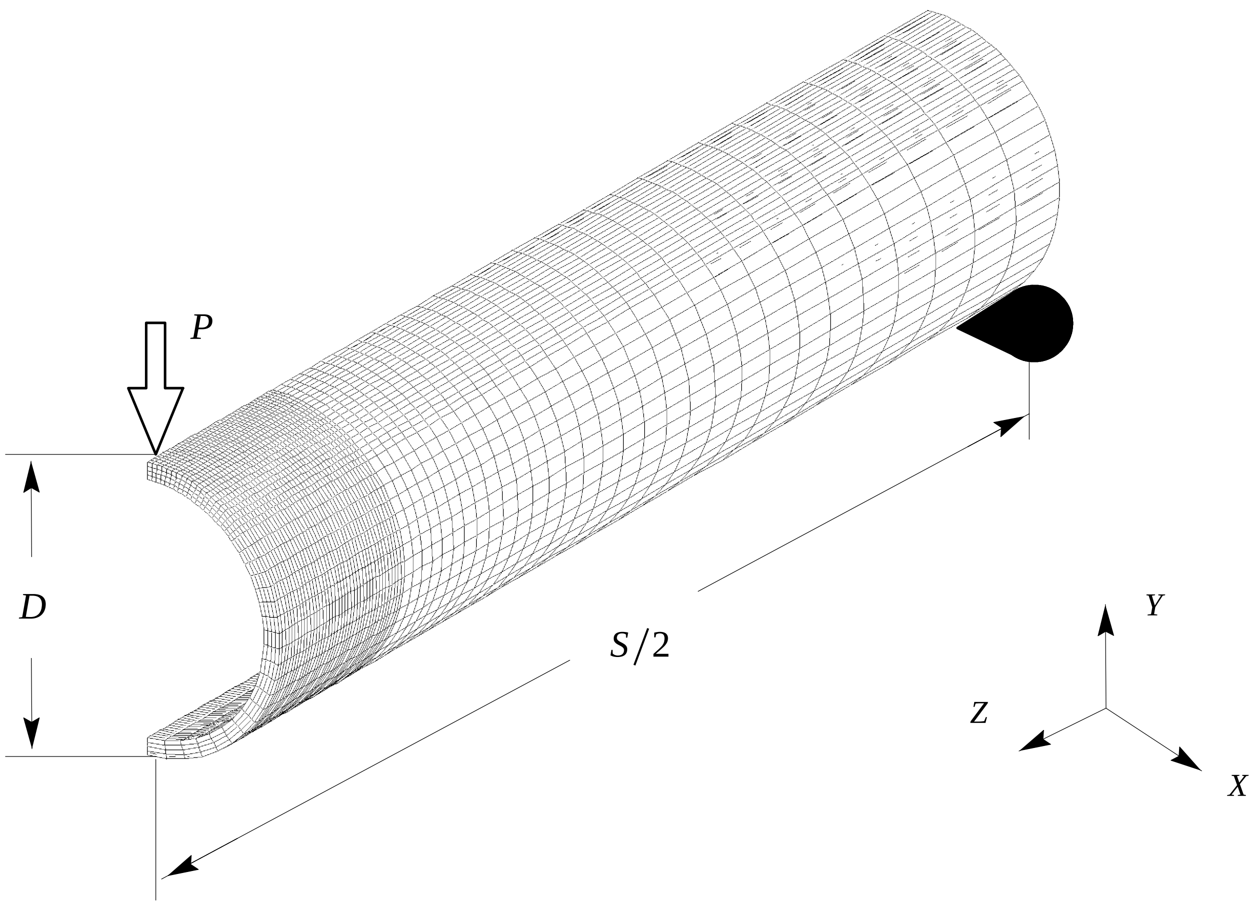

Figure 5 *Quarter symmetric, 3D finite element model for the simply supported tested pipe with S = 1000 mm.*

the indentation process progresses, the numerical simulation captures almost every detail of the experimentally measured curves.

Figure 6(b) compares the numerical predictions with the experimental results for the axially loaded pipe specimens ($S = 1000$ and 3000 mm) with $T = 12$ and 24 tf. Similarly to the results previously presented, there is good agreement between the experimental measurements and the numerical predictions. Moreover, the effect of axial tension on the structural response for the pipe specimens is correctly described by the numerical analysis. For a fixed dent depth value, there is a relatively weak dependence of lateral load on axial force T.

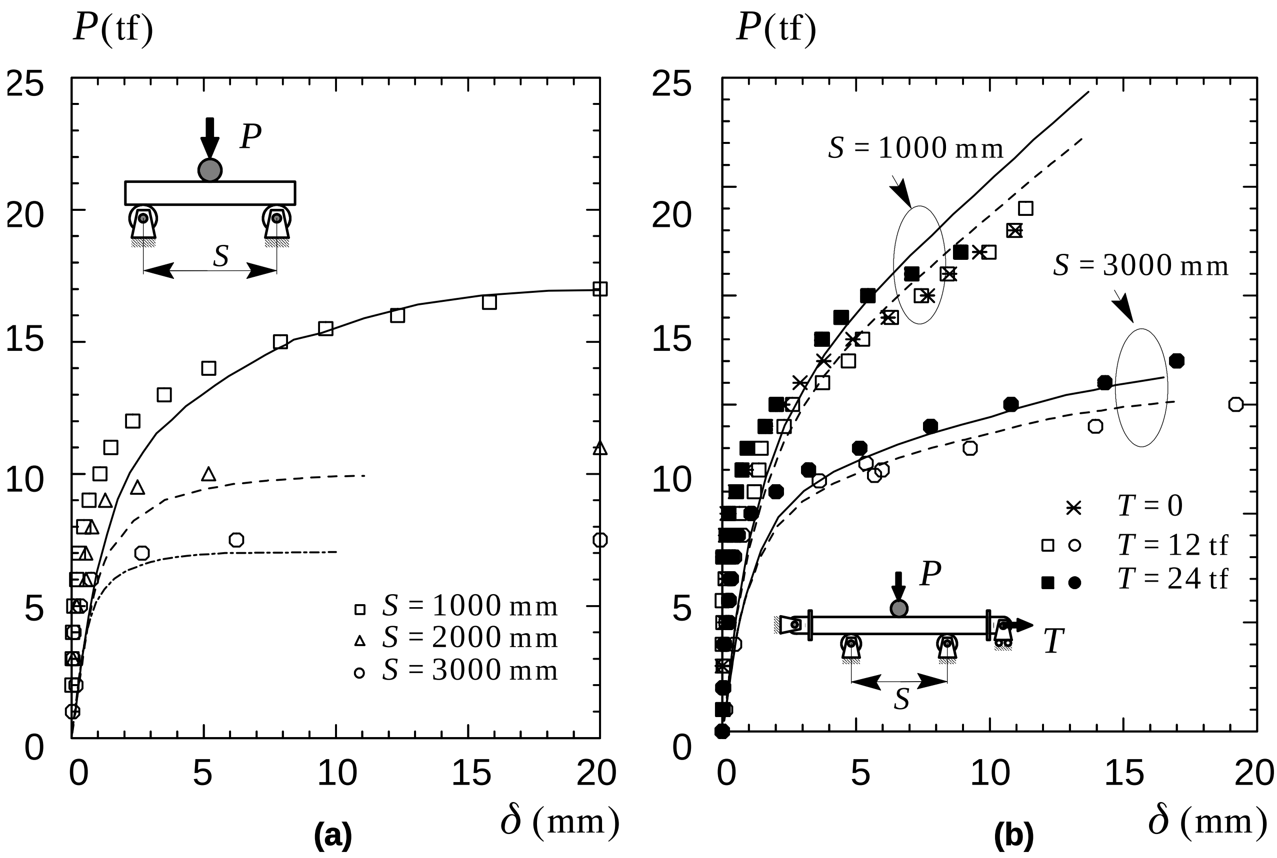

Figure 6 *Numerical predictions of indenter load vs. dent depth: (a) simply supported tested pipes; (b) axially loaded pipes.*

4.2. Comparison with Simple Analytical Approaches

This section examines the applicability of simple analytical procedures to describe the structural response of the tested pipes. To address this issue, we consider the widely adopted relationship between load and dent depth developed by Ellinas and Walker [4] in the form

$$P = \frac{K}{4}\sigma_{ys} t^2 \left(\frac{\delta}{D}\right)^{1/2} \tag{2}$$

where P is the dent (impact) force, δ is the dent depth, σ_{ys} is the material yield stress, D is the pipe (outside) diameter and t is the pipe wall thickness. Here, K is a constant defined by Ellinas and Walker [4] as 150 for stress given in MPa and thickness in mm with the force expressed in N. The above expression builds upon a rigid plastic analysis of a thin-walled cylinder which is also adopted in damage assessment procedures for offshore structures specified by API RP 2A [3].

Figure 7 compares the load-dent depth response predicted by Ellinas and Walker [4] with the experimental measurements for all pipe configurations ($S = 1000$, 2000 and 3000 mm). The agreement between experiments and Eq. (2) is evident for small values of dent depth ($\delta \approx 1 \sim 2$ mm). However, for larger values of dent depth ($\delta \gtrsim 2$ mm), Eq. (2) predicts unrealistic increasing loads with increased values of δ. Moreover, even for moderate dent depth values ($\delta \approx 5$ mm which corresponds to ~4% of pipe diameter), the predicted dent forces differ by a factor of 2 to 5 from the experimental measurements. Clearly, this behavior severely restricts the application of Eq. (2) to dents of 1~2% of pipe diameter.

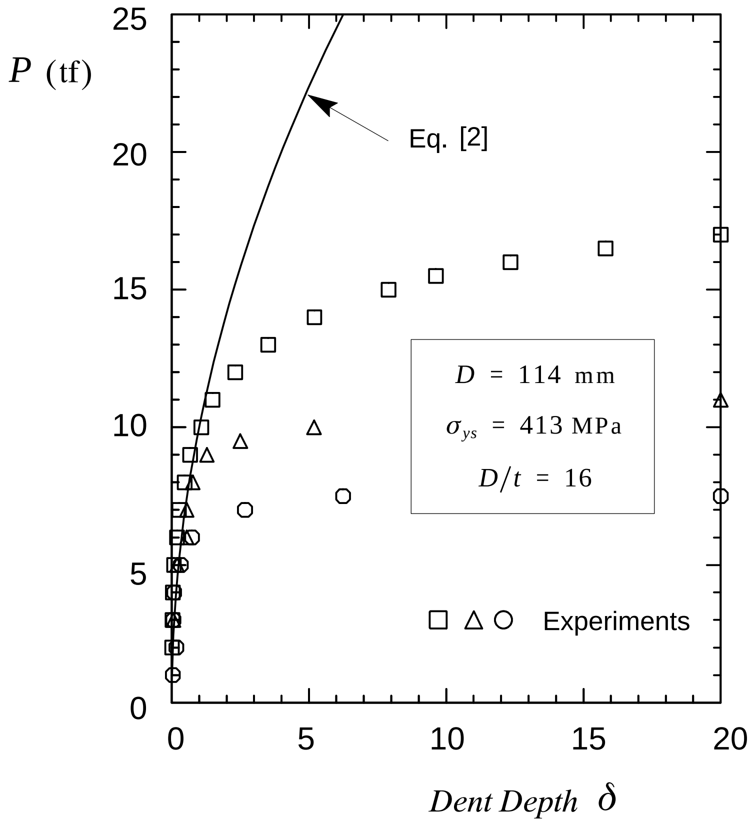

Figure 7 *Prediction of load-dent depth response given by Eq. (2) for the tested pipes.*

5. Numerical Analysis of a Production Riser

To examine the effects of dent damage on the load-carrying capacity of a typical production riser, this section presents key results of parametric analyses conducted on steel tubes ($D = 9\ 5/8$") with varying length (load span) $S = 1000$, 2000, 3000 and 6000 mm, and diameter to thickness (D/t) ratio. Moreover, the analyses also include the potential effects of the axial traction forces on the load-dent depth response which arise in top tensioned risers. The material flow properties correspond to a typical structural steel applicable in marine risers (*e.g.,* API X60): $n = 10$ and $E/\sigma_0 = 500$ with $E = 206$ GPa and $\nu = 0.3$.

Figure 8(a) provides the evolution of dent depth with increased dent force for varying load spans. The similarity of the numerical results with plots presented previously is evident. The curves rise rapidly for small values of dent depth ($\delta \approx 2 \sim 4$ mm) and then more slowly for increased values of dent depth until the maximum load (structural collapse) is reached; for the load span $S = 6000$ mm, the instability points corresponds to $\delta \approx 10$ mm. As already noted, this behavior is due to the strong interaction of the denting process with the global bending fields that develop in the tubes with increased loading. The reduced plastic modulus section coupled with large plastic rotations significantly reduces the nominal plastic limit load. This contrasts sharply with the relationship between load and dent depth given by Eq. (2) developed by Ellinas and Walker [4] as displayed in Fig. 8(a).

Figure 8(b) presents the evolution of dent depth with increased loading for varying riser diameter to thickness (D/t) ratio with load span $S = 3000$ mm. While the general trends displayed by these curves are essentially similar to the structural behavior presented previously, the discrepancies between Eq. (2) and the numerical predictions become even larger with decreased D/t-ratios. Since this equation was derived by considering a rigid plastic analysis of a thin-walled cylinder, the analytical solution for thicker tubes (smaller D/t-ratios) will exhibit a more pronounced departure from the elastic-plastic, 3D finite element solutions presented here.

Figure 8(c) provides the evolution of dent depth with increased loading for varying axial traction forces (top tension) with load span $S = 3000$ mm. While increased values of top tension causes a corresponding increase in the dent force for a fixed value of δ, this effect is small as demonstrated by the numerical results. Such behavior can be understood in terms of the weak dependence of the local stiffness (well at the region where the indentation process takes place) on the top tension.

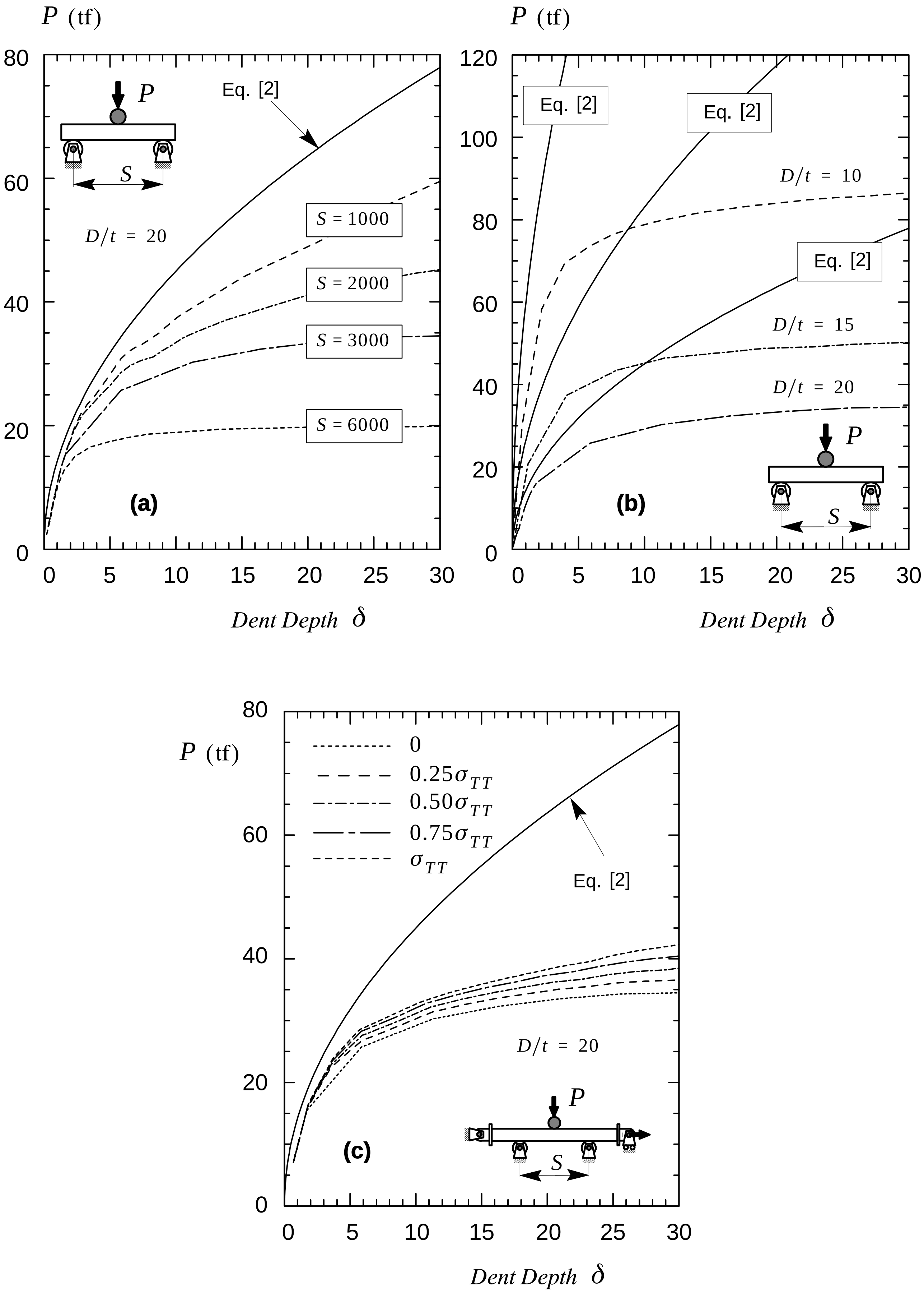

Figure 8 *Load vs. dent depth response for a 9 5⁄8" riser: (a) with varying load spans S = 1000, 2000, 3000 and 6000 mm; (b) for different D/t−ratios; (c) for different axial tension loads.*

Unlike the global riser behavior (such as, for example, vibration modes), which does depend on the applied top tension, the localized indentation process is much more affected by the flow properties of the material (yield stress and hardening behavior) and geometrical properties (D/t-ratio and load span) than the axial traction forces.

6. Concluding Remarks

This study describes an experimental and numerical investigation of dented pipes under lateral loading which is representative of structural damage that occurs in tubular members and marine risers after collision and impact loads. Testing conducted on a 4 1⁄2" O.D. (114 mm) API N80 pipe (580 MPa yield stress) with varying length demonstrates that the growth of the dented region produces a significant reduction of the pipe modulus section which strongly affects its load-carrying capacity. The large plastic region that develops during the indentation process controls the large energy-dissipation capability of the steel pipe during the performance of plastic work by the lateral load.

The 3D finite element analyses employed to simulate the large deformation, non-linear behavior for the tested pipes correctly predict the structural (plastic) behavior and the instability for these tubular structures. These numerical analyses also convincingly demonstrate that analytical approaches based upon rigid plastic models using idealized conditions provide unrealistic predictions of the load-dent depth response for dent depth larger than $\sim 2\%$ of the pipe thickness. This suggests that guidelines for dent damage assessments based upon such analytical approaches should be used only for small values of dent depth ($\delta \approx 1 \sim 2\%$ of pipe diameter).

Extensions of this study to include other effects of dent damage on the structural integrity of marine risers are currently underway. For example, effects of very large plastic deformation at the dent region on ductile cracking and material failure are particularly important. Another important area of interest is the assessment of dynamic effects which arise from the global behavior of the colliding structures on the dent damage of marine risers. While the focus of the present work is restricted on the *post collision* damage (*i.e.*, assessment of the remaining load-carrying capacity after the impact) based upon a quasi-static lateral load, more realistic evaluation of structural dent damage should consider the actual dynamic loading which arises during the riser-to-riser collision. These research efforts, when taken together, will provide a fairly extensive body of results which enable the development of improved design criteria for tubular members and risers.

Acknowledgements

This investigation is part of a research project supported by Petrobrás. Permission to publish the experimental results is gratefully acknowledged.

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