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CORRODED PIPELINES: AN APPROACH TO CONSIDER LOCAL EFFECTS INTO GLOBAL ANALYSIS

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Abstract. The objective of this work is to present a simplified approach to solve corroded pipelines using 1-D finite elements. The local effects are evaluated *a-priori* by 2 or 3D computational models with axi symmetric, shell or brick finite elements. These effects are considered by the stress concentration factors (SCF) which depend on damage types. The stress magnification is introduced in the 1D finite element model artificially. One is possible to show that the equilibrium equation is no more attempted and the interactive process is no more convergent unless a compensative procedure is adopted. This methodology and many applications are presented here to show that the procedure is efficient and has practical applications, especially for long structural systems.

1 INTRODUCTION

Pipes are used for oil and gas transportation for long distances, crossing areas and fields with difficult access. When corrosion damage is detected, it is important to consider the changing of affected member. The substitution is not trivial since the fluid transportation is stopped and, in general, it is not easy to access the local affected by corrosion.

Sometimes, it is preferable to analyze the residual integrity of the pipe using experimental methods, semi-analytical methods or simulating the structure and the surrounding soil by computational methods like the finite element method.

Most of the computational models are developed using two (axi-symmetric elements) or three dimensional elements (shells or brick elements). The last ones are preferable since they can better represent the thickness variation of the pipe due to the corrosion. Many articles can be found in the literature using this approach, some of them are calibrated by experimental values and showed good approximation with the measured values of deformation, stress field and, specially, the ultimate pressure (Choi *et al*, 200; Chiodo *et al*, 2008; Oh *et al*,2007).

Although three dimensional models can represent and capture better the local effects due to stress concentration, however, in a long pipe segment, with many corroded regions, the computational effort can be very high. In these situations, it would be advantageous the use of beam elements or line elements, based on beam theories. The question is how to introduce local effects in the line (beam) elements, if they are not able to consider depth variation in the original formulation? An interesting way could be the enhancement of the displacement fields by high order polynomial functions or trigonometric functions, as in the generalized finite element methods. The other way is to evaluate the local effects in simple three dimensional models and introduce the result in a one-dimensional model as stress concentrations (Shang, 2009; Shang *et al*, 2009). This is the approach of the present work. The objective is to introduce the local effects in beam elements by stress concentration factors (SCF). The SCF are determined previously in three-dimensional analysis and introduced into one dimensional model, which are analyzed until the rupture pressure. This approach is simpler than three dimensional models and, as will be shown, presents very satisfactory results. The proposed technique may be applied for any types of damaged beams, but it is easier to be applied for pipes elements due to their simple geometrical sections, even when a defect is presented.

Pipes are systems of cylindrical tubes, which are used for fluid transportation for long distances. Due to their geometrical dimensions, and considering the case of landing pipes (not sub sea pipes), they may treated as a rigid structure, without oval deformation of transversal section, when small deformations are presented. For high pressures, the tube walls can be flow and residual deformations may appear. Critical situations are observed in the case of damaged tubes, especially when the corrosion appears. In the neighborhood of damaged regions, plastic strains are present and, probably, the collapse could occur there. Corroded pipes are subjected to stress concentration which produces high level of stresses in local regions. Plasticity may initiate in these regions and, in the sequence, will affect regions nearby to these ones.

Some hypotheses are considered here: the tube is perfect cylindrical, with semi-thick walls. The most important effects are the longitudinal and circumferential ones. There is not oval deformation. The non linear effects are due to the plastic deformations (non linear physical analysis) and due to high deformation (non linear geometrical analysis) in the corroded region, before the plastic collapse.

The type of the corroded region has any geometry, dimensions and depth. In this work, it will be presented some particular cases (rectangular and spherical defects), which are the most considered in the literature (Choi *et al*, 2003).

The damaged region is defined by polar coordinates and may be found in any position. More than one corroded regions can be treated in the same section.

Since the present approach is based on the stress concentration factors which are included *a-priori* in the finite element model, it is clear that stress values will be evaluated with good precision, but deformation will incorporate some mistakes. By the way, these mistakes are not relevant since the focus is the collapse pressures assessment.

The SCF are determined by previous three-dimensional analyses, using quadratic brick elements. The SCF curves are plotted for many points in the damage region, to permit the evaluation of the stresses. These curves are generated as in the elastic phase than in plastic phase, allowing the application of progressive pressures (Kim and Son, 2004).

The SCF curves are determined for many load configurations, for example, internal pressure, external pressure, axial tensions, bending, and so on. Some cases of tubes, with different thickness, diameter, radius, and damage depth, length, are presented in this work.

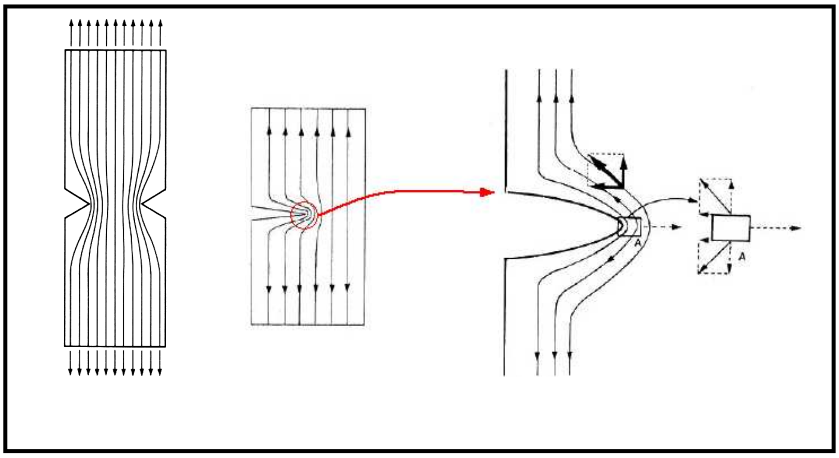


Figure 1 – Forces trajectory in a damage plate.

2 STRESS CONCENTRATION FACTORS

Geometrical imperfections, such as corrosion, may cause stress concentration on pipes. In the neighborhood of corroded regions, the stresses are amplified depending on the loading type. The ratio of amplified stress for damaged tube and the normal stress for non damaged tube is known as stress concentration factor (SCF). The SCF relates the maximum stresses for the both cases (damaged and non damaged) at the same point (Kim and Son, 2004).

To understand this concept, consider the forces trajectory as illustrated in Figure 1. When a body is loaded, internal forces appear to guarantee the equilibrium condition in all parts. If there is not any damage, the internal forces has smooth trajectory and theirs values can be determined by analytical or approximated methods. But, when there is a local effect such as corrosion, the trajectory lines are perturbed and approximate one to the other, amplifying the stress magnitudes. If the load increases, it could cause material plasticity or even the premature rupture than the non damaged tube case.

Stress concentration may be found in some of the following situations:

a) Thickness abrupt reduction, due to original design or due to corrosion;
b) The local point of applying forces, due Saint-Venant phenomenon;
c) Discontinuity of different materials;
d) Residual stresses as a result of thermal process during manufacturing;

e) Cracks due to the process of manufacturing or during a loading.

The “V-shape” defect shown in Figure 1 produces a higher stresses when the corner ratios become smaller. Sometimes, with the objective to reduce the stress intensity, it is common to increase the corner ratio or even to remove part of the materials of the body.

One of the pioneer work in the stress concentration was published by Neuber (ap ud Villar, 2002). Neuber analyzed a prismatic bar with V-notched defect subjected to torsion. The non linear stress strain relations was utilized and, based on experimental results, Neuber wrote:

$$K_\sigma K_\varepsilon = K_t^2 \tag{1}$$

where

K_ε is the strain concentration factor, $K_\varepsilon = \dfrac{\varepsilon_{\max}}{\varepsilon_{nom}}$; K_t is the elastic stress concentration factor; and K_σ is the plastic stress concentration factor. Note that, during elastic phase, we have $K_t = K_\sigma$. By this way

$$K_t^2 = \frac{\sigma_{\max}}{\sigma_{nom}} \times \frac{\varepsilon_{\max}}{\varepsilon_{nom}} \tag{2}$$

Only in the linear case the three factors are the same, that is, $K_t = K_\sigma = K_\varepsilon$. The Figure 2 shows the variation of the stress and strain concentration factors. Neuber had also proposed that this condition could be generalized with good approximation for two or three stress states using any fault theory.

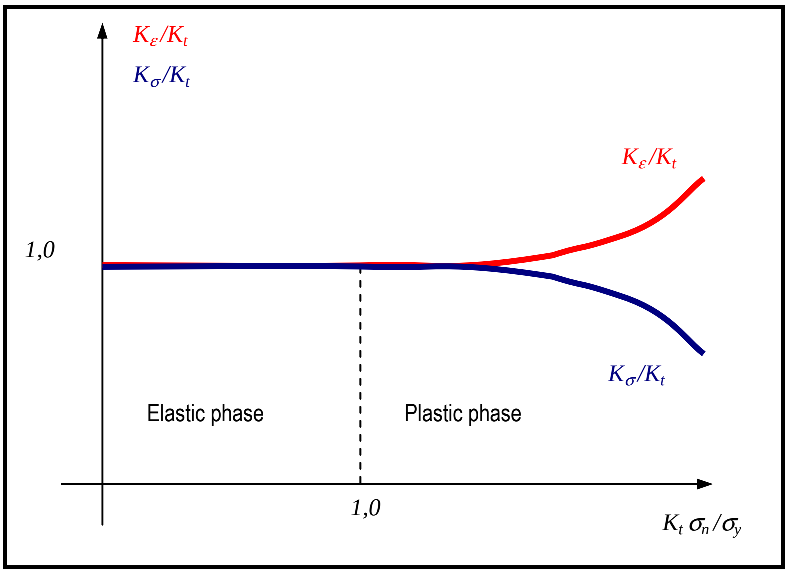


Figure 2 – Neuber rule (*ap ud* Villar, 2002) applied in the root of notch.

Figure 3 shows two tubes with and without defects and the stress distribution along the wall. It is possible to see that, at the same point *P*, the stress in the damaged case is greater than the undamaged. While the stress concentration factor is uniform and constant near the point *P* for the first case, the same not occurs for second case, because the variation of *K* with the position *x* and the loading *F*.

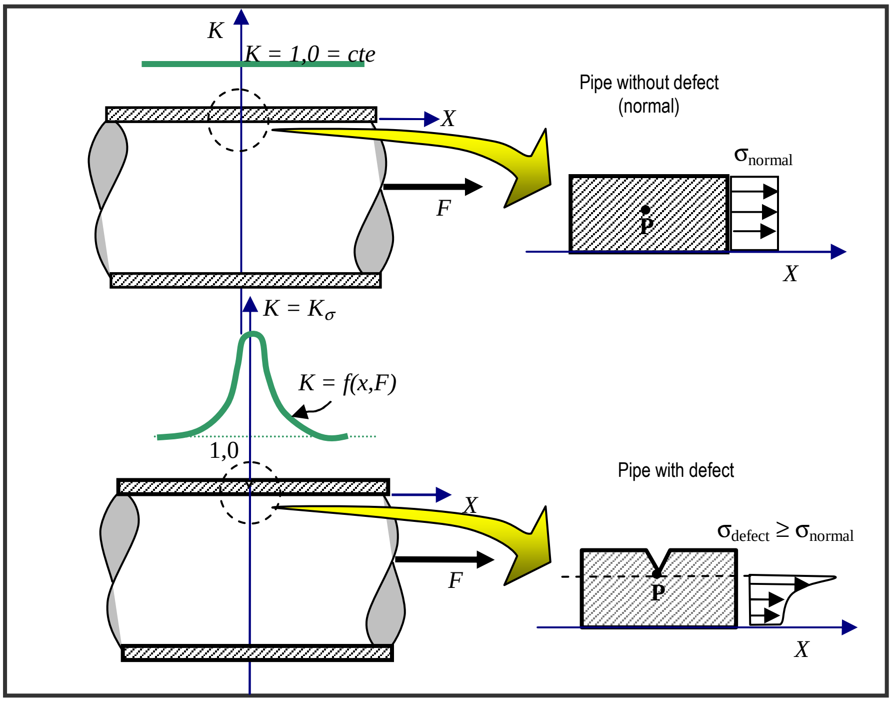


Figure 3 – Stress distribution along the tube thickness for normal (without defect) and damaged pipes.

3 THE COMPENSATION METHOD FOR SCF

With the intention to enhance beam model with stress concentration effect, the purpose of this work is to incorporate the SCF in the virtual work equation, and solve the nonlinear equation using Newton-Raphson method. In order to fulfill this purpose, it was necessary some algebra arrange.

Consider the virtual work equation for beam model:

$$\int_{^0V} {}^{t+\Delta t}_{0}S_{x_1}\, \delta^{t+\Delta t}_{0}\varepsilon_{x_1}\, d\,^0V + \int_{^0V} {}^{t+\Delta t}_{0}S_{\theta}\, \delta^{t+\Delta t}_{0}\varepsilon_{\theta}\, d\,^0V = \delta^{t+\Delta t}W_{ext} \quad (3)$$

Where ${}^{t+\Delta t}_{0}S_{x_1}$, ${}^{t+\Delta t}_{0}\varepsilon_{x_1}$, ${}^{t+\Delta t}_{0}S_{\theta}$, ${}^{t+\Delta t}_{0}\varepsilon_{\theta}$ are the stresses and strains in the longitudinal and transversal directions.

In order to incorporate SCF in this equation, consider initially the stress increment equation below. Observe that, when there is not any stress concentration effect, the SCF is equal to 1. If it happens, then the stress increment equation returns to its original form.

$${}^{t+\Delta t}_{o}S_{x_1} = {}^{t}_{o}S_{x_1} + k_{\sigma}\, {}_{o}S_{x_1} \;\rightarrow\; {}^{t+\Delta t}_{o}S_{x_1} = {}^{t}_{o}S_{x_1} + {}_{o}S_{x_1} + (k_{\sigma} - 1)\, {}_{o}S_{x_1} \quad (4)$$

$${}^{t+\Delta t}_{o}S_{\theta} = {}^{t}_{o}S_{\theta} + k_{\theta}\, {}_{o}S_{\theta} \;\rightarrow\; {}^{t+\Delta t}_{o}S_{\theta} = {}^{t}_{o}S_{\theta} + {}_{o}S_{\theta} + (k_{\theta} - 1)\, {}_{o}S_{\theta} \quad (5)$$

One is possible to conclude that SCF is a function of point position, stress ratio and stress increment ratio, just as showed by equation (6). Thus, it is possible to obtain the function of SCF by interpolation from results evaluated from commercial software, such as ANSYS. This methodology was employed considering that SCF of each point would not affect the results in the SCF assessment of other point. Obviously, this is just a simplified method.

$$k = f\left(X(x,r,\theta), \Delta\sigma/\Delta\sigma_{nom}, \sigma_{máx}/\sigma_{esc}\right) \tag{6}$$

In the assumption of thin wall pipe, the stress in considered as constant in radial r direction, which yields to $k = f\left(X(x,\theta), \Delta\sigma/\Delta\sigma_{nom}, \sigma_{máx}/\sigma_{esc}\right)$.

Introducing the equations (4) and (5) in the equation (3), which results in:

$$\begin{aligned}&\int_{^0V}\left({}_o^tS_{x_1} + {}_oS_{x_1} + \left(k_\sigma - 1\right){}_oS_{x_1}\right)\delta\,{}^{t+\Delta t}_{0}\varepsilon_{x_1}\,d\,{}^0V + \\ &\int_{^0V}\left({}_o^tS_\theta + {}_oS_\theta + \left(k_\theta - 1\right){}_oS_\theta\right)\delta\,{}^{t+\Delta t}_{0}\varepsilon_\theta\,d\,{}^0V = \delta\,{}^{t+\Delta t}W_{ext}\end{aligned} \tag{7}$$

However, to implement this methodology of multiply the stress increment by SCF, the global equilibrium condition will be disturbed and the solution process will not converge. Consider the condition as show in figure 4. The equilibrium condition is attained when the sum of force and momentum is zero. For the convergence criteria used in this work, the internal energy of body is equal to external energy produced by external force.

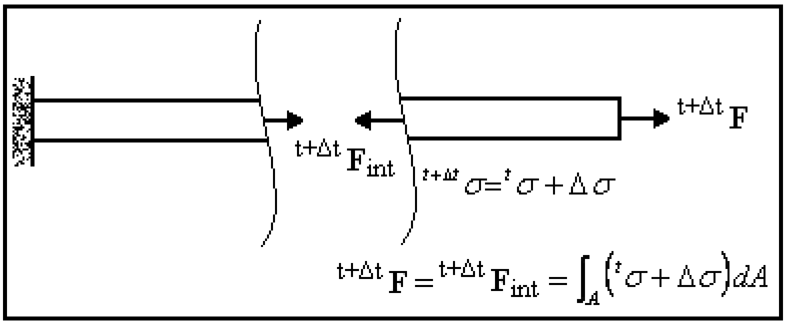


Figure - 4 Equilibrium condition of the beam without corrosion.

Once introduce artificially SCF in the solution process to multiply the stress increment, and then the equilibrium condition is not more satisfied. The reason is that the SCF introduce a extra positive quantity during solution process. This quantity is evaluated by multiplication of stress increment with the factor $(k-1)$, just as shown in Figure 5. In order to attain equilibrium of Virtual Work Equation, and at the same time, attain to the convergence criteria, the intention is to eliminate this extra quantity. Thus, the internal force is evaluate by the equation (8), furthermore, the virtual work equation (7) can't be assessed only introducing equations (4) and (5), but it is necessary to add in the external work side, the extra quantity of energy created artificially by SCF, as showed by equation (9). It is just like to sum a energy quantity in the left hand side, and sum the same quantity at the right hand side of equation (3). In other words, from mathematic point of view, there were nothing modified in equation (3). In this way, the equilibrium criteria will be attained.

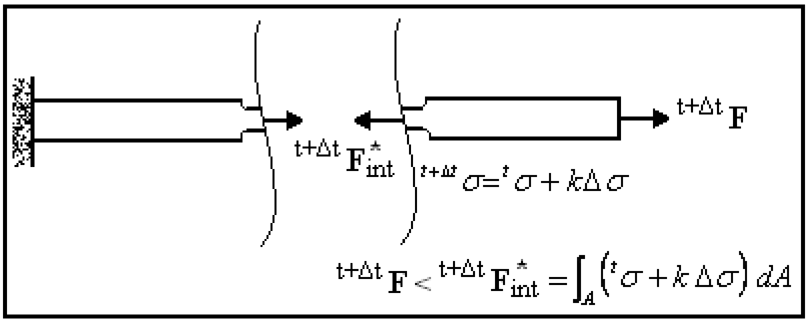


Figure 5 - Equilibrium condition unattained with the beam with defect.

$$ {}^{t+\Delta t}F^{*}_{\text{int}} = \int_{A} \left({}^{t}\sigma + k\Delta\sigma \right) dA - \int_{A} (k-1)\Delta\sigma \, dA \tag{8} $$

$$ \begin{aligned} &\int_{{}^{0}V} \left({}^{t}_{o}S_{x_1} + {}_{o}S_{x_1} + \left(k_{\sigma} - 1\right) {}_{o}S_{x_1} \right) \delta^{t+\Delta t}_{0}\varepsilon_{x_1} \, d^{0}V + \\ &\int_{{}^{0}V} \left({}^{t}_{o}S_{\theta} + {}_{o}S_{\theta} + \left(k_{\theta} - 1\right) {}_{o}S_{\theta} \right) \delta^{t+\Delta t}_{0}\varepsilon_{\theta} \, d^{0}V = \delta^{t+\Delta t}W^{*}_{ext} \end{aligned} \tag{9} $$

4 DETERMINATION OF STRESS CONCENTRATION FACTORS (SCF)

Models 3D are used to generate SCF. For each case, two different analysis must be developed, the first one with the undamaged pipe and the second one with the corroded pipe. Both meshes must be the same, excepted in the damaged region, where there are finite elements only in the perfect model. A set of points are picked from the damaged boundary. These points will be used to calculate the SCF.

In this section, three examples will be presented. The defects are semi-circular, and rectangular. Although the constitutive relation may be anyone, here one is supposed that the materials are bi-modular, that is, they have two linear phases, the first one with Young modulus E_1 = 205 MPa (for stresses less or equal to 420 MPa) and the second one with E_2 = 75 MPa (for stresses bigger than 420 MPa). The Poisson ratio is 0,25.

4.1 Pipe with uniforme semi-circular defect.

To determine the local stress distribution, it has been carried out a numerical model based on the finite element method. The first application is related to a uniform semi-circular defect. The pipe geometrical and mechanical properties are: outer diameter - 762 mm; wall thickness – 17,5 mm; defect depth: 75% of thickness. The defect is supposed to be along a circunferencial line.

Two different loads are applied: uniform internal pressure and longitudinal traction. The pipe is submitted to internal pressure with 30 MPa. The longitudinal traction is applied uniformly at the end of tube with magnitude of 0,1 MPa, while the opposite end is fixed. The non linear computational analysis is made with 300 steps for the first case and 100 steps for the second. Figure 6 shows the finite element mesh. In order to reduce the solution time, symmetry boundary conditions are considered. Figure 7a and 7b show the meshes for damaged and the perfect cases and a sequence of four points is indicated to measure the stresses. One is observed that de points P1 to P4 are exactly the same for both meshes.

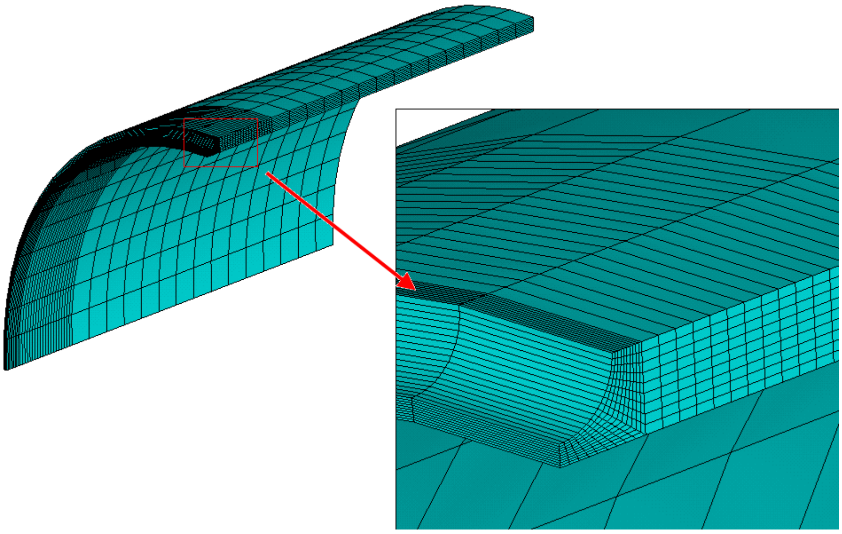
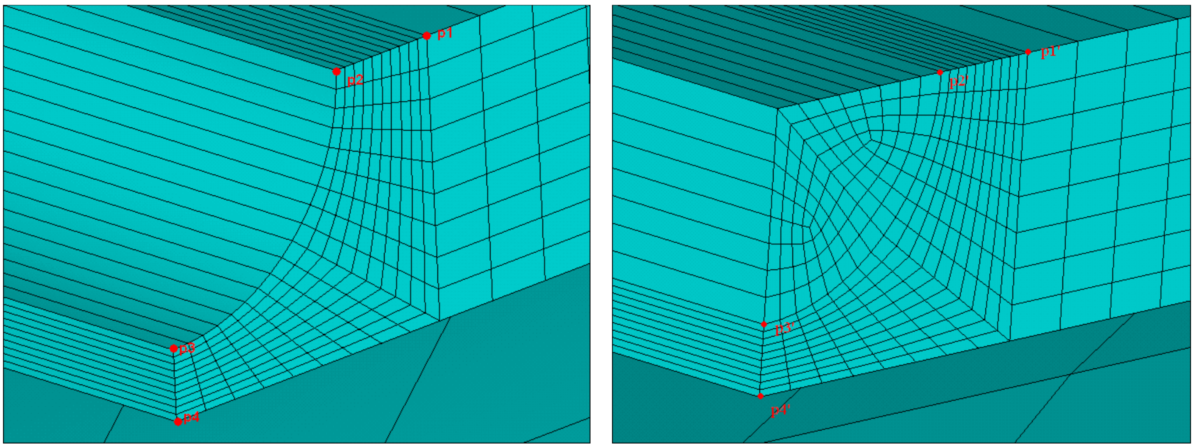


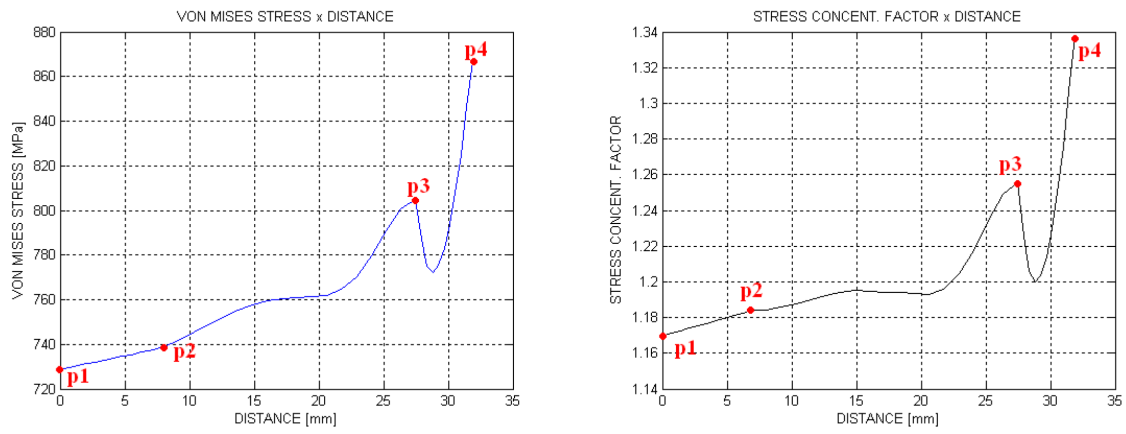
Figure 6 – Finite element mesh for uniform semi-circular defect.

The stress distribution from points P1 to P4 is shown in Figure 8a. The corresponding stress concentration factors for each point are shown in Figure 8b for the last step of analysis. It is interesting to see the similarities of stresses and SCF from points P1 to P4. The distance between each point is measured along the same path line. For the end traction load case, the results are plotted in Figure 9a and 9b. One is noted that, changing the load case, the stress distribution is modified, as well as the SCF, for the same type of defect.



(a) (b)

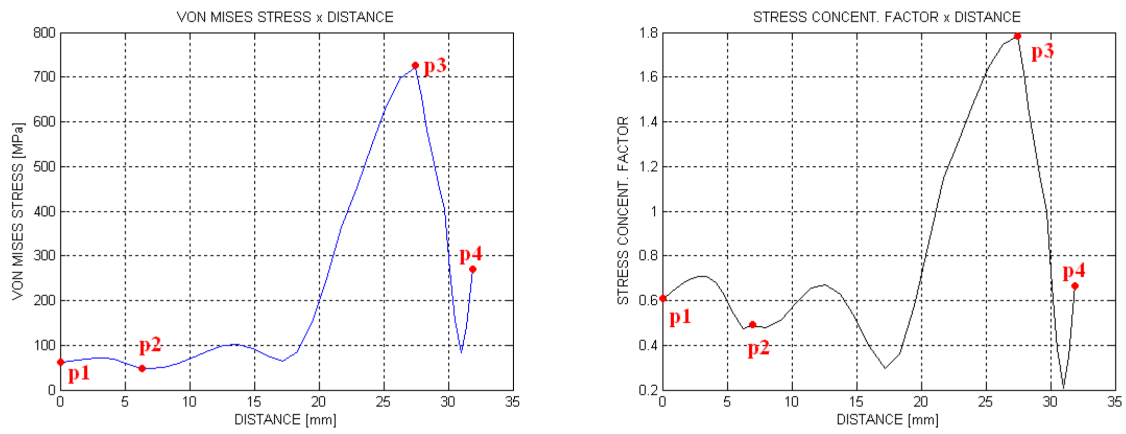
Figure 7 – Finite element meshes for (a) damaged case; (b) normal case.



(a) (b)

Figure 8 – Damaged pipe subjected to internal pressure: (a) Stress magnitude; (b) Stress concentration factors.

It is important to note the difference between tangential (circumferential) and longitudinal stresses. Figure 10 shows the curves of distance versus stress concentration factor for both cases. For the tangential stresses, it is observed smooth variation between P1 to P4 in the stress concentration factor magnitude. For the longitudinal stresses, the variation is bigger than the other case and the maximum value is determined at point P3 with SCF near 1,8. A simple approach is to adopt the SCF as is equal the maximum value found. To refine the model, it would be better to adopt two different SCF for each point, one for tangential and other for longitudinal stresses. However, if the Von Mises criterion is used, then both effects are considered.



(a) (b)

Figure 9 – Damaged pipe subjected to end tensions: (a) Stress magnitude; (b) Stress concentration factors

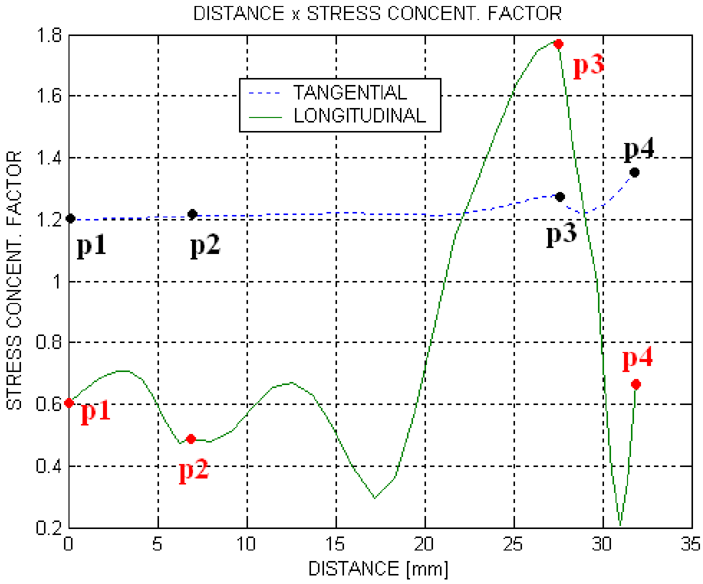
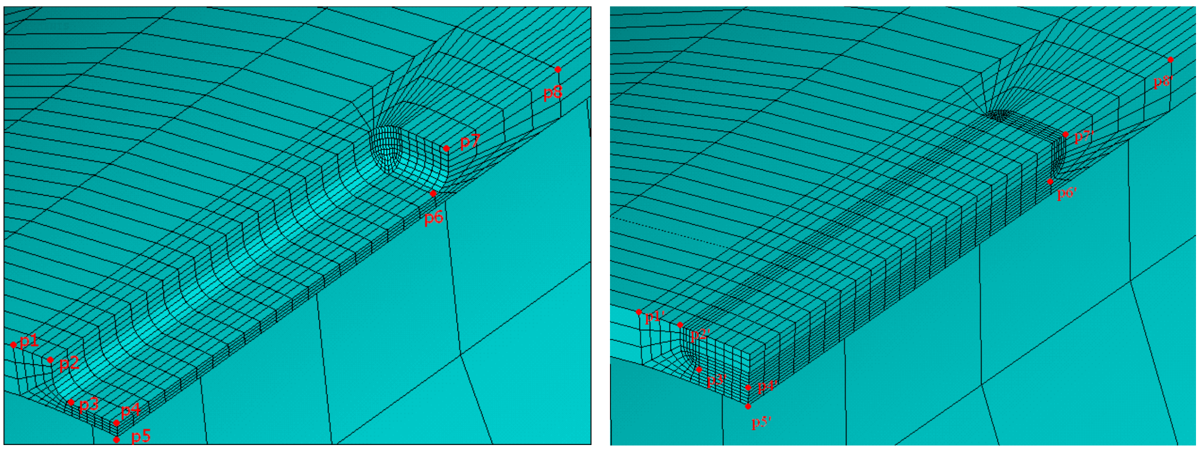


Figure 10 – Difference between longitudinal and tangential stress concentration factors for end traction load.

4.2 Pipe with rectangular defect

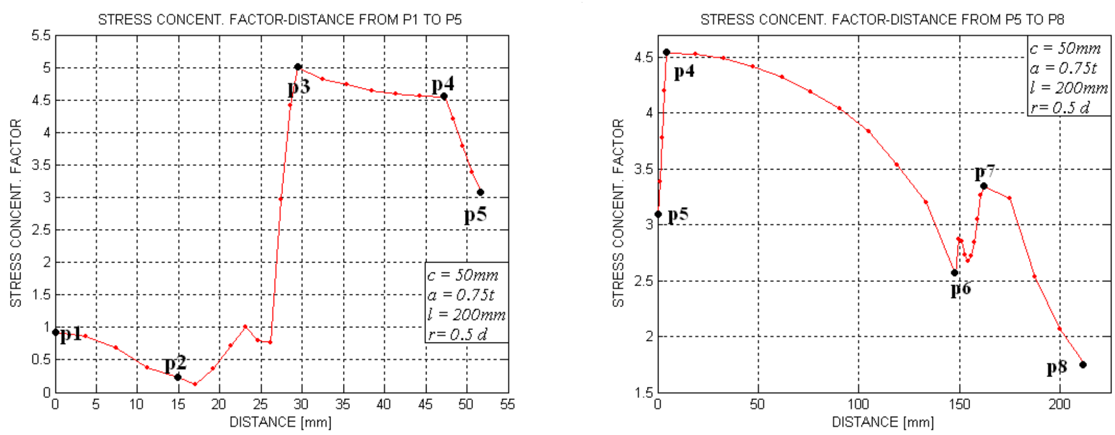
The next case to analyze is pipe with rectangular defect. In this example, the same pipe analyzed by Choi *et al* (2003) is considered. The geometrical data are: pipe length – 2300 mm; outer radius – 381 mm; wall thickness – 17.5 mm; defect width – 50 mm; defect length – 300 mm; defect depth – 75% of thickness.

In this case, eight points are selected to determine the stresses, as can be seen in Figures 11a and 11b for both situations, damaged and perfect pipe. Again, the points are exactly the same for both cases. Figures 12a and 12b show the SCF's from points P1 to P5 and from P5 to P8. One is observed two orthogonal directions between P1-P5 and P5-P8. These SCF were calculated using Von Mises stresses. The maximum SCF is in point P3.



(a) (b)

Figure 11 – Sequence of points P1-P2-P3-P4-P5 and P5-P4-P6-P7-P8 for (a) damaged rectangular pipe and (b) normal pipe.



(a) (b)

Figure 12 – SCF for (a) points P1-P5, (b) P5-P8 of rectangular damaged pipe.

5. ANALYSIS OF APPLICATION OF STRESS COMPENSATION METHOD WITH SOFTWARE APC3D

The purpose of this section is to study stress concentration factor in a specific point and discuss how the factor behaves during material yielding. A FORTRAN software was developed named APC3D, the “Corroded Frame Analysis-3D software”. Beam elements with three nodes and a total of eight degree of freedom for 3D analysis were de included in the package. The software solve linear and non linear analysis, using Newton Raphson procedure.

5.1 Pipe with uniform semicircular defect subjected to traction

Consider a hypothetic pipe subjected to traction and has a semicircular uniform defect. The pipe has 200 mm of external diameter; 190 mm for internal diameter; 100 mm for length. The defect is located in the middle of pipe and has a ratio 2,5 mm.

One of the ends is supposed totally restricted and, in the other end, a force of 500 kN is applied. For non linear analysis, the Newton-Raphson method is employed and 50 increments were used to divide the load. In order to construct the model, axi symmetric elements have been used to create the mesh to reduce computational effort and time for iterative and incremental solution. Bi modular material, as described in section 4, is adopted here. The stress configuration in the 50 steps is showed in Figure 13.

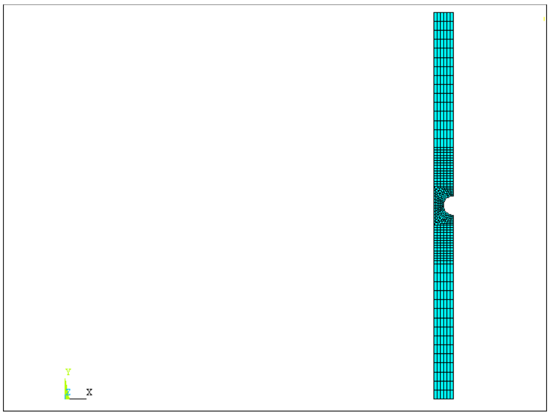


Figure 13 (a) - Mesh of model

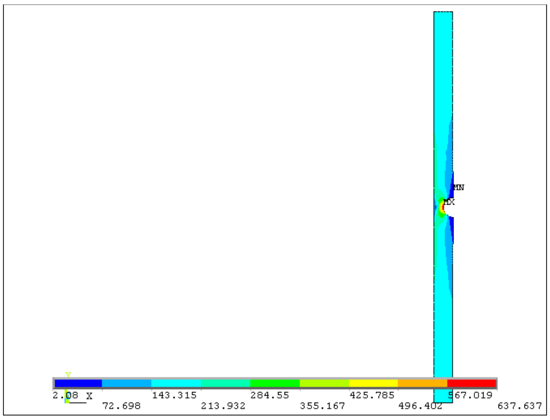


Figure 13 (b) - Stress distribuition.

According to Figure 13, the maximum stress is located at the root of defect. The stress field at the vicinity of this point suffers an increase caused by stress concentration effect. In order to study furthermore the stress concentration effect, a curve of stress at the defect root is obtained in function of load increment. After that, another pipe case was modeled with the same configuration in the software APC3D. At this time, the beam element is used and the corroded part is model as an element with thinner wall thickness, considering the internal diameter as the same as the other element. The stress evaluated at this element was plotted as function of load increments. Then, dividing the maximum stress of ANSYS by stress assessed by APC3D, it is possible to obtain the SCF function. To visualize the effect of this factor at the moment of plastic state, a graphic is plotted relating the maximum stress and the yield stress, which is constant and equal to 420 MPa. One is possible to observe that in linear state, the stress concentration factor (SCF) is almost constant, however, when the ratio $\sigma_{\max}/\sigma_{esc}$ >1, the SCF begins to decrease.

Introducing the SCF in the software APC3D and analyze the case of pipe subjected to traction, the stress at the root of defect (P3 of figure 14) is assessed and compared to a same stress curve obtained by ANSYS. This comparison yields to Figure 15.

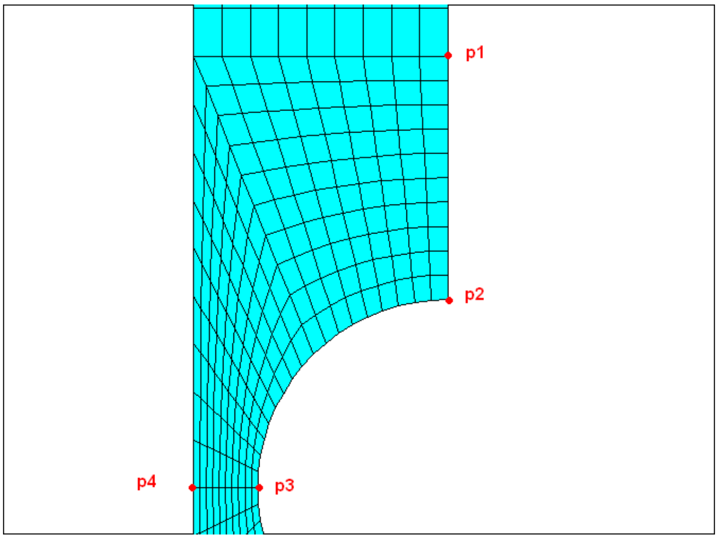


Figure 14 - Finite element mesh compost by axi symmetric elements and principal points position.

One observes that, in the linear behavior, the stress compensation method is capable to solve the problem caused by extra stress introduced by stress concentration factor. For this reason, the stress assessed by APC3D is similar, or almost equal to the stress calculated by ANSYS. Nevertheless, after the yield stress, the situation is different. The first reason is due the lack of knowledge on how the stress concentration factor participates in the Von Mises surface expansion, which characterizes the inelasticity bilinear material behavior.

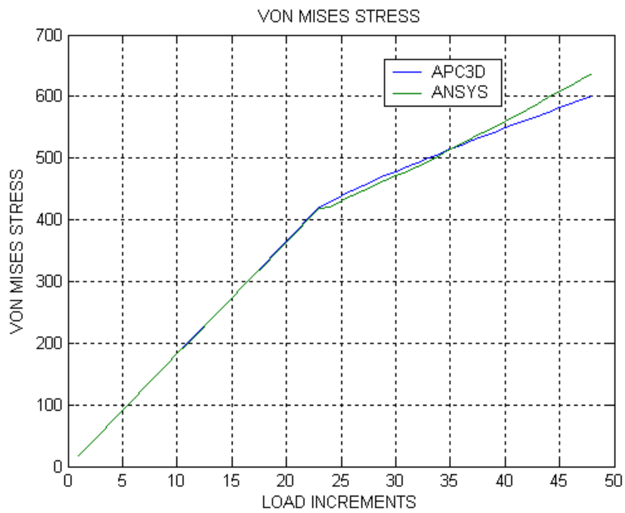


Figure 15 - Comparison of stress curve obtained by APC3D and ANSYS at the defect root.

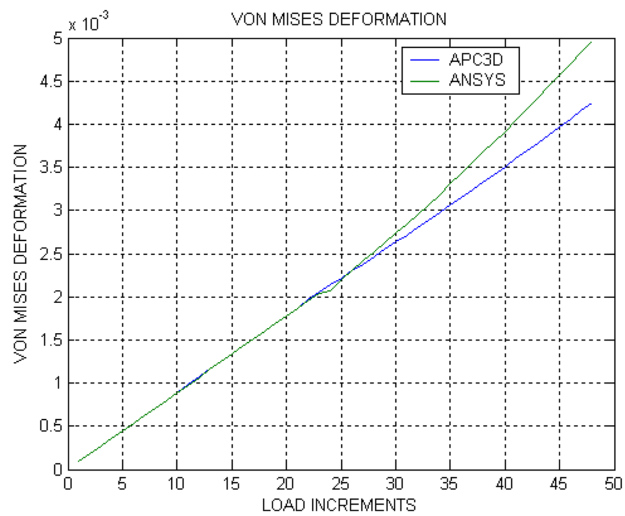


Figure 16 - Comparison of deformation curves obtained by ANSYS and APC3D.

Similarly, the deformation calculated by APC3D considering deformation concentration factor was compared with that obtained by ANSYS, as can be shown in Figure 16. In this case, the relative difference is higher then stress's one. The numerical error could be generated during the interpolation of stress concentration factor function.

Other parameter, such as displacement, is important to be evaluated. Nevertheless, different from stress and deformation, the displacement wasn't be multiplied by concentration factor. In the analysis down by APC3D, a point of analysis was considered at the root of defect. The displacement measured at this point was compared with the same point located at the same position in the ANSYS model. The result of this comparison is presented by Figure 17.

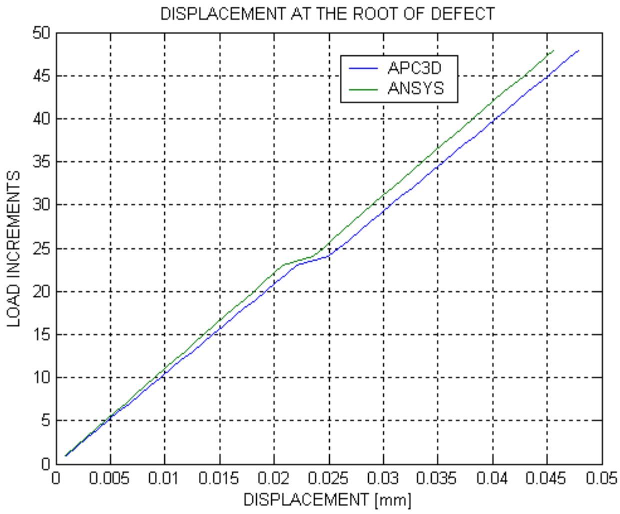


Figure – 17. Comparison of displacement curve obtained by APC3D and ANSYS.

5.2 Pipe with semicircular uniform defect subjected to internal pressure

For the effect of analysis, consider a pipe with same property and same dimension as showed before in pipe with uniform semicircular defect, and the mesh similar to the one shown in Figure 4. The pipe is subjected to an internal pressure with magnitude of 25 MPa and in numerical model; the load was divided into 25 increments. The same methodology was employed for analysis of pipeline subjected to internal pressure. Two different evaluation methods are compared in the APC3D, the first with tangential SCF and the other without tangential SCF. Observe that the result without tangential SCF is totally different from that encountered by ANSYS. However, the proposed assessment method in the present work, which incorporates tangential SCF function, has obtained the result approximately to the ANSYS model. The SCF is evaluated at each increment, and the curve for this factor was obtained by using stress increments ratio. This methodology is particularly interesting when the behavior of stress – deformation curve is nonlinear, just as the case in that the pipe is subjected to internal pressure. The comparison of result of stress obtained by APC3D and by ANSYS is showed in the Figure 18.

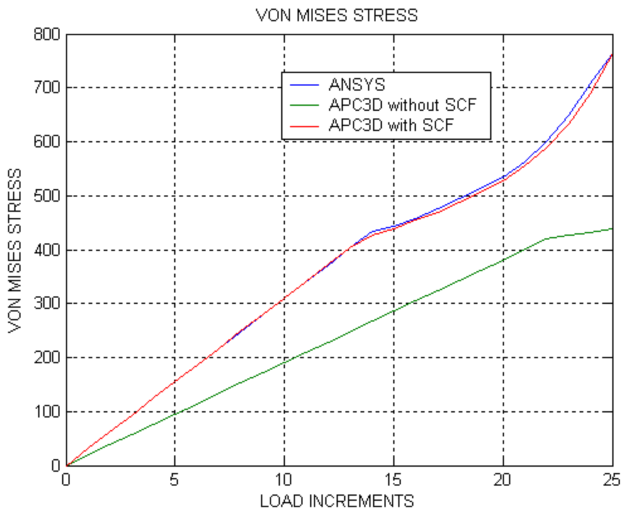


Figure 18 - Von Mises stress of pipe subjected to internal pressure.

5.3 Pipe with rectangular defect subjected to internal pressure

In this model, Point 4, as indicated in Figure 11, is considered as the point of interest. The Von Mises stress curve as the function of increment step at point 4 is assessed by ANSYS. Based on stress curve, an interpolation process has been carried out in order to evaluate stress concentration curve and incorporate in software APC3D. The numerical model is composed by 23 elements in the APC3D application. And the corrosion is modeled by an element with the length equal to the corrosion length. The result of analysis in Von Mises stress at the point 4 is presented by Figure 19 in function of internal pressure. It is possible to observe that the stress concentration factor is an important parameter which affects the stress assessment when the pipe has corrosion. There is a significant difference in the result when incorporate SCF in the methodology or not.

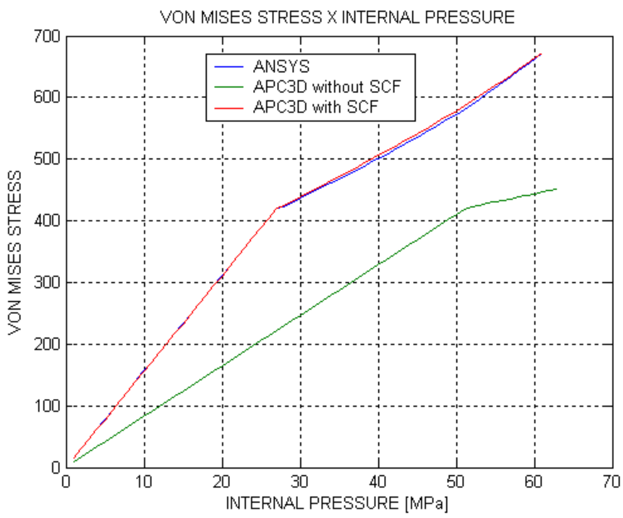


Figure 19 - Von Mises stress × internal pressure

6. CONCLUSIONS

The proposed method is able to represent stress variation in a corroded pipe. Good results are expected for stresses and the compensation method is fundamental to guarantee the convergence of numerical solution. However, displacements and strains incorporate mistakes, since the SCF change artificially only the stresses. Since the focus is to evaluate the stress field and to determine the residual stresses, these mistakes are not essential. The non linear behavior is captured appropriately by the proposed method. So, for long systems of pipelines, the local effects can be introduced into 1-D numerical models as the methodology proposed in the present paper. For future works, one is suggest preparing a menu of different SCF curves, whose may be used as alternative for different corroded types.

Based on the analysis down with the methodology developed by this work, it is possible to observe the possibility to carry out local analysis in a global analysis model by incorporating SCF function in the software APC3D. Such application could reduce the model constituted with three dimensional element in a model using only one dimensional model. Consequently, reduce the model solution time.

However, the proposed methodology presents several limits. Implicitly, numerical errors were incorporated due the fact that the SCF was introduced artificially in the Virtual Work Equation. Such error is accumulated during the evaluation of Von Mises surface expansion. Additionally, other numerical error is produced by inaccuracy of SCF function during the interpolation process.

The solution for Virtual Work Equation is down by assessment a priori of nodal displacement. Once the displacement is evaluated, the sequence step is to evaluate the deformation, then the stress increment. The methodology present in the present work can be calculated with acceptable accuracy the stress after application of stress concentration factor in the beam model. However, the deformation and displacement are not assessed with same accuracy level. Such inaccuracy is generated by difficulties in determine deformation and nodal displacement based on final stress. This limitation is inherent in the finite element formulation adopted in the present work.

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8. REFERENCES

Choi, J. B.; Goo, B. K.; Kim, J. C. Development of Limit Load Solutions for Corroded Gas Pipelines. *Int J. Pressure Vessels and Piping.*, v. 80, p.121-128, 2003.

Chiodo, M. S. G.; Ruggieri, C. Previsão da pressão de falha em dutos contendo defeitos de corrosão: critérios de colapso e validação experimental. V Congresso Nacional de Engenharia Mecânica, Bahia, 2008.

Dmytrakh, I. M.; Pluvinage, G.; Qilafku, G. On corrosion fatigue emanating from notches: stress field and electrochemistry. Materials Science, v. 37, No. 2, 2001.

Forti, T. L. L.; Requena, J. A.; Devloo, P. R. B. Formulação de viga 3D com relação constitutiva não-linear. Anais XXVIII CILAMCE - Congresso Ibero Latino Americano sobre Métodos Computacionais em Engenharia, Porto, 2007.

Kim, Y. J.; Son, B. G. Finite element based stress concentration factors for pipes with local wall thinning. International Journal of Pressure Vessels and Piping, Kyonggi-do, v. 81, p. 897-906, 2004

Kim, S. E.; Kim, Y.; Choi, S. H. Nonlinear analysis of 3D steel frames. Thin-Walled Structures, v. 39, p. 445-461, 2001.

Nowzartash, F.; Mohareb, M. An elasto-plastic finite element for steel pipelines. International Journal of Pressure Vessels and Piping, v. 81, p. 919-930, 2004.

Neuber, H. Theory of stress concentration for shear-strained prismatic bodies with arbitrary nonlinear stress-strain law. Journal of Applied Mechanics, 1961.

Oh, C. K.; Kim, Y. J.; Baek, J. H.; Kim, Y. P.; Kim, W. S. Ductile failure analysis of APIX65 pipes with notch-type defects using a local fracture criterion. International Journal of Pressure Vessels and Piping, v. 84, p. 512-525, 2007.

Shang, H. S; Machado, R. D.; Abdalla Filho, J. E. Análise simplificada de sistemas de dutos pressurizados pelo MEF considerando os efeitos de concentração de tensões produzidos pela corrosão. CILAMCE 2009, Iberian Latin American Congress on Computational Engineering, Búzios – RJ, Brazil, 2009.

Shang, H. S. - Introdução de fatores de concentração de tensões na análise não linear via MEF de sistemas de dutos corroídos. Dissertação de Mestrado. Programa de Pós-Graduação em Engenharia Mecânica, Pontifícia Universidade Católica do Paraná, 2009.

Villar, M. F. Estudo dos modelos de concentração de tensões através do auxílio de técnicas numéricas de modelagem. Tese de M. Sc., Pós-graduação em Engenharia Aeronáutica, Instituto Tecnológico de Aeronáutica, São José dos Campos, SP, Brasil, 2002.