

## AUTOMATIC MODELING AND ANALYSIS OF PIPELINES WITH COLONIES OF CORROSION DEFECTS

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**Abstract.** The prediction of the failure pressure (FP) of pipelines with corrosion defects is the most important issue in structural integrity analysis of high pressure pipeline systems. The Finite Element Method (FEM), provides accurate results in failure pressure prediction. However, the FEM modeling and analysis process of a single pipeline with idealized corrosion defects could take weeks, and it is very repetitive and requires highly specialized engineering. In other work Cabral, H.L.D. (2007) presents a set of computational tools called PIPEFLAW for automatic generation of Finite Element (FE) models of pipelines with idealized corrosion defects. This work presents a new option for automatic generation of FE models with corrosion defects arbitrarily located along the pipeline. These tools are based on the MSC.PATRAN pre and post-process commercial software and the data input to the pre-processor is done through a friendly graphical user interface. The ANSYS software is used for physical and geometric al non-linear analysis to obtain the failure pressure value. The FP obtained by the automatic generated models, is compared with experimental results obtained by burst tests (Benjamin et al, 2005; Benjamin et al, 2006a) and numerical results obtained by manually generated models (Andrade et al, 2006). The obtained results validate the automatic procedure and the FE models built.

## 1. INTRODUCTION

During the operation of pipelines, most accidents originate from corrosion defects. The accurate prediction of the failure pressure (FP) of pipelines with corrosion defects is one of the most important issues in structural integrity analysis of high pressure pipeline system, including onshore and offshore installations. To avoid loss of lives, and also economic, social, environmental, and image damages to the company, a large effort is being directed to the mitigation of corrosion damage as well as to its monitoring. Many methods for FP prediction in pipelines with corrosion defects are available, such as numerical techniques based on the FEM and experimental burst tests.

However, the FEM modeling and analysis process requires highly specialized engineering and specific software knowledge and experience. Besides that, the modeling process of a single pipeline with idealized corrosion defects could take weeks and it is a very repetitive and monotonous procedure, and therefore it is very prone to error. In other work, CABRAL (2007) presents a set of computational tools called PIPEFLAW for the automatic generation of Finite Element (FE) models of pipelines with a single idealized corrosion defect or multiple corrosion defects longitudinally aligned or circumferentially aligned, that can be analyzed in some common commercial FE software. These models are generated considering a few parameters describing pipe dimensions, defect position and defect dimensions. These tools are based on the MSC.PATRAN pre and post-process commercial software, the code was written with PCL (Patran Command Language).

This work describes a new functionality in the PIPEFLAW system for automatic generation of FE pipe models with corrosion defects in arbitrary positions, located on the internal or the external pipe surface, considering the mesh transitions rules presented in (CABRAL, 2007; CABRAL et al, 2007; MOTTA et al, 2008; MOTTA et al, 2009), or defining different mesh transitions rules. In past work (MOTTA et al, 2009) some model limitations existed in the program, mainly, related to the spacing between adjacent defects. In this work a new procedure is described to automatically generate FE models of pipes with very close corrosion defects arbitrarily located in the pipe. This new feature enables the analysis of pipeline containing colonies of corrosion defects.

The data input to the pre-processor is done through a friendly graphical user interface (buttons, menus and text boxes for data capture), where the pipe dimensions, defects dimensions and defect locations for multiple defect cases can be given.

The generated models can be analyzed by several common commercial programs that use the Finite Element Method (FEM). In this work, ANSYS is used for physical and geometrical non-linear analysis to obtain the FP. The FP numerically obtained by the automatically generated models, is compared with experimental results obtained by burst tests (Benjamin et al, 2005; Benjamin et al, 2006a) and numerical results obtained by manually generated models (Andrade et al, 2006).

## 2. PIPEFLAW PROGRAM

The PIPEFLAW program includes a set of functions and graphical interface classes implemented in PCL language to generate automatically FE pipe models with corrosion defects following some predefined standards adopted by PETROBRÁS R&D Center (CABRAL, 2007). These standard procedures can be modified in the most recent version of the program. The input data for the automatic generation of pipe models is done entirely by graphical user interface (GUI) tools.

## 3. MODEL GENERATION

The first step to build the pipe model with defects in an arbitrary configuration consists in generating each defect box along the pipe following the procedure described in detail in Cabral (2007). In order to do this, a previously implemented subroutine to generate a quarter of an isolated defect region is used (see Figure 1). The default number of solid elements along the wall thickness inside

the defect region computed by the program is four. The element length along the thickness is used as a parameter to compute automatically the number of elements along the remaining edges of the solids of the model. This produces an aspect ratio about unit for the elements inside the defect region, as illustrated in Figure 1. In this figure  $T$  is the pipe thickness,  $D$  is the defect depth,  $LC$  and  $LL$  are, respectively, the defect width and length,  $RA$  and  $RC$  are the fillet radii.

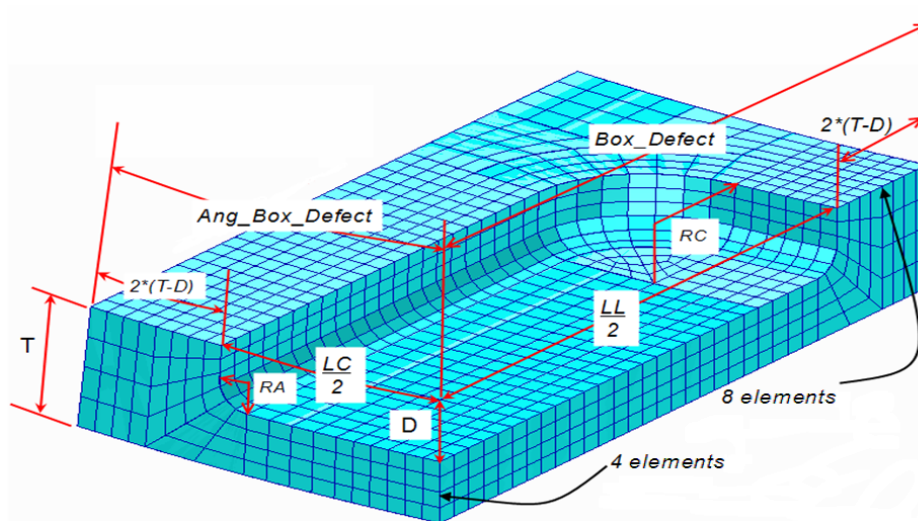


Figure 1: Default mesh generated by the PIPEFLAW in the defect region.

The full defects are then completed (through symmetry operations), providing a box containing the local mesh (Figure 2(a)) for each defect. In the next step the defect boxes are placed in their final positions by rotation and translation operations, as shown in Figure 2(b).

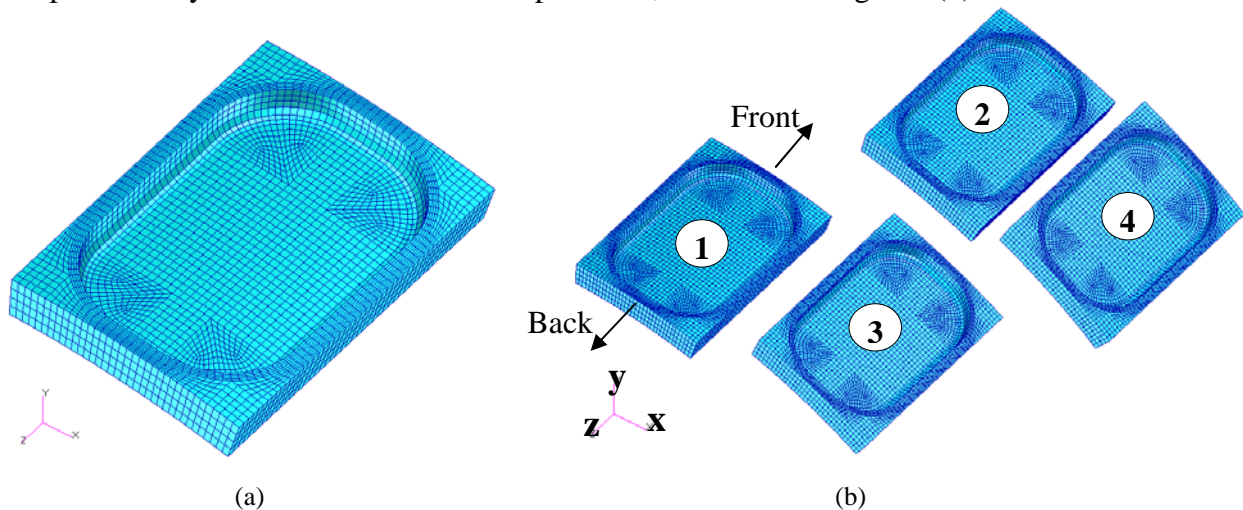


Figure 2: Generation of defect mesh boxes on their proper position:  
(a) generating a complete isolated defect mesh box and (b) locating the defect mesh boxes.

To obtain a complete consistent mesh for the whole pipe, compatible with the already properly located set of defect mesh boxes, we go through the circumferentially ordered groups, building solids in both longitudinal (axis  $z$ ) directions (front and back, see Figure 2(b)) and then generating finite element meshes inside the solids. Each of these solids is created using a developed function whose input data are the four vertices of the solid on the external pipe surface. Those four points can either already exist or can be generated during the process. Some of the important stages re-

quired in this process will be described in the next sub-section, but for further details please consult Motta et al (2008).

### 3.1 Longitudinal Intersection – Pre-processing stage

To generate the front (-z) and back (+z) solids, see Figure 2(b), for each defect box, a pre-processing procedure is performed to find out which defect boxes interact with each other along the two directions, i.e. using the defect boxes positions (longitudinal and circumferential coordinates) it is verified for each defect, on front and back direction through longitudinal projection, which other defect boxes intercept it. By considering “0” a virtual defect box when no interference occurs, i.e. moving longitudinally, front or back, only the pipe extremity (or boundary) is found (see Figure 3). This procedure results in the intersection matrices (Motta et al, 2008), which are used to generate the solids and meshes in regions between defects. In Figure 3 a sketch of the multi-defect configuration presented in Figure 2(b) is presented showing the frontal intersection of each defect box.

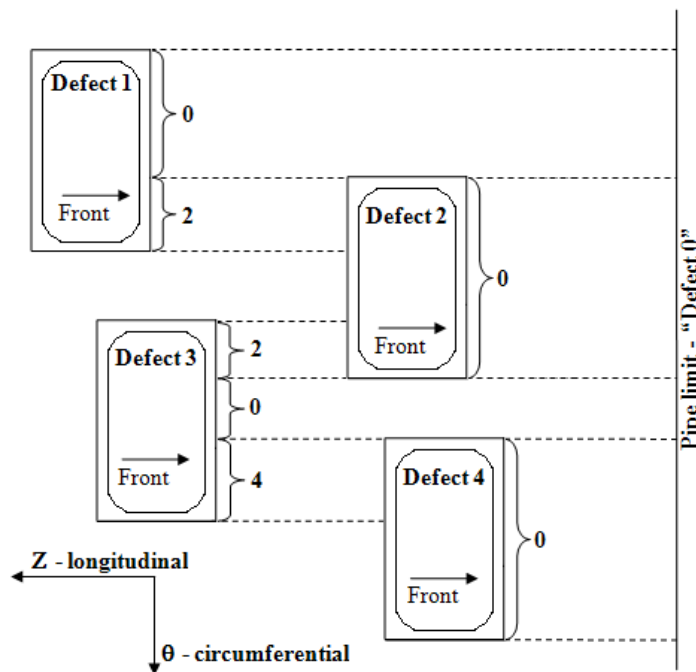


Figure 3: Longitudinal defect boxes frontal interferences.

### 3.2 Building the connections between defect boxes

The connections are generated based on the intersection matrices created in the pre-processing stage. Accordingly, consider the configuration shown in Figures 2(b) and 3, the first longitudinal frontal connection for defect box 1 link it to “defect box” 0. The three solids created for such connection are depicted in Figure 4.

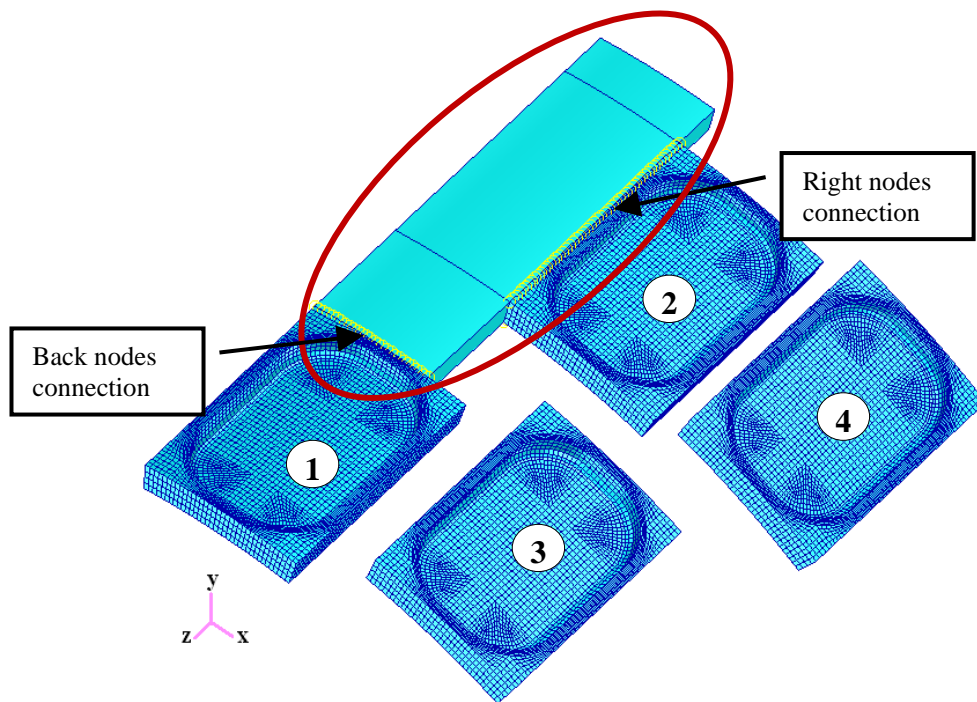


Figure 4: First longitudinal frontal connection for defect box 1 (connecting “1” to “0”).

To generate all the required solids inside a connection between the defect boxes, we need to find out, for each connection, which and where are the existing nodes that will be part of such connection, in order to generate the solids and meshes. This procedure is carried out based on the intersection matrices. Knowing that, and if required creating extra nodes (on the external surface), the solid is obtained by extruding the four external surface nodes to the internal surface. The creation of extra nodes is required as not always the connections have all required nodes to define the solids. Depending on which sides we have pre-existing nodes, one of the fifteen different possible situations to generate the connection is defined (once again the reader is referred to Motta et al (2008) for further details).

Figure 5 shows the generation of all required connections to get the complete defect regions or defect colony region, for the configuration described in Figure 2(b). First we obtain each connection, and corresponding solids, without the mesh, and then the mesh is generated inside the already defined solids, so that we can follow step-by-step how the defect colony region is built.

Far from the defect colony region, the mesh does not require the same discretization than the region near the defects, where there is more stress concentration. Thus, following the defect colony region creation the transitions regions are created around that, in order to reduce the element density. After the number of transition regions necessary to achieve the desired element size, the element size is kept constant. In this application, four surface transitions and one thickness transition are employed.

The Figure 6 illustrates the model after the complete process, the Figure 6(a) show the entire pipe model, whereas Figure 6(b) focus in the transitions region considered.

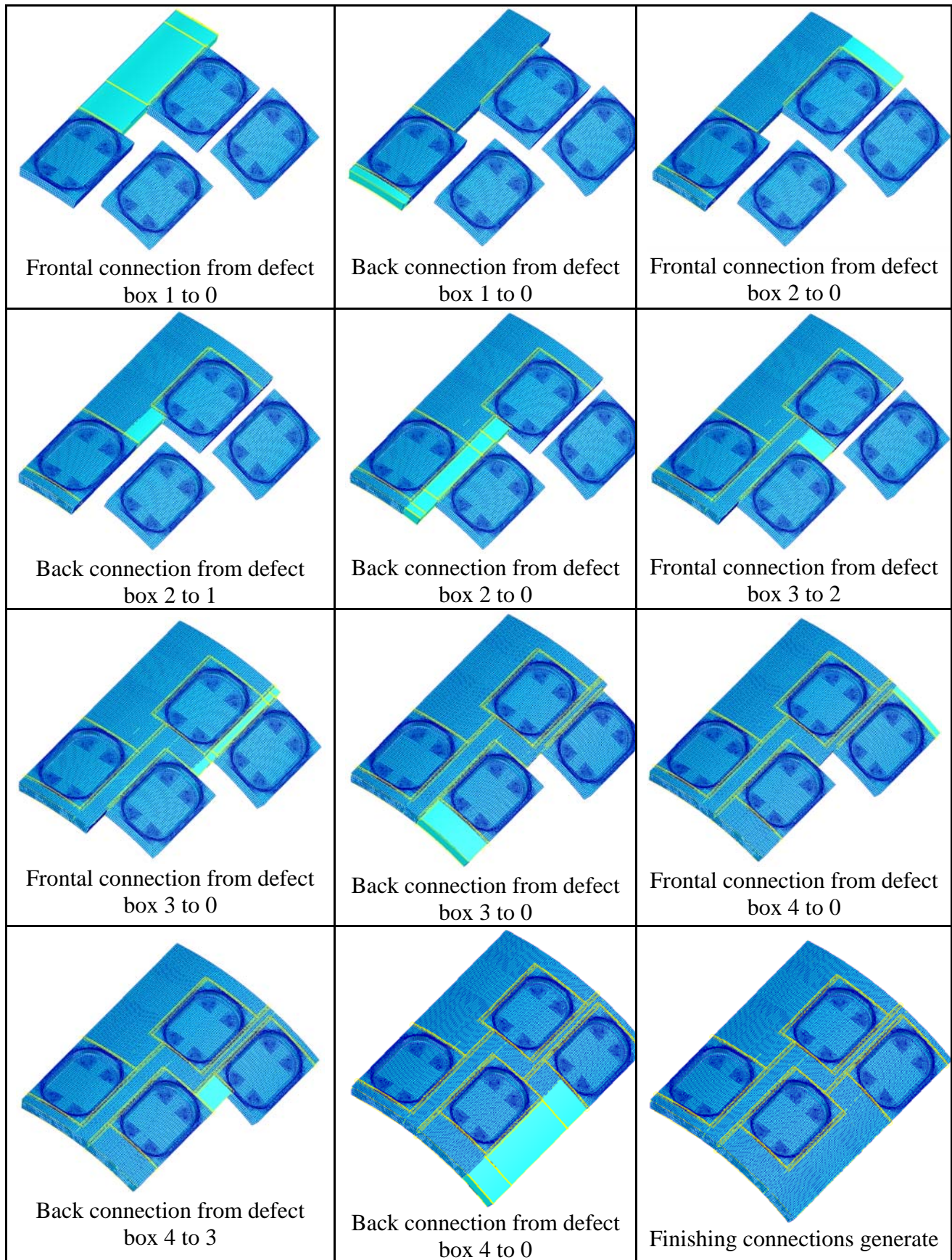


Figure 5: Step-by-step model generation.

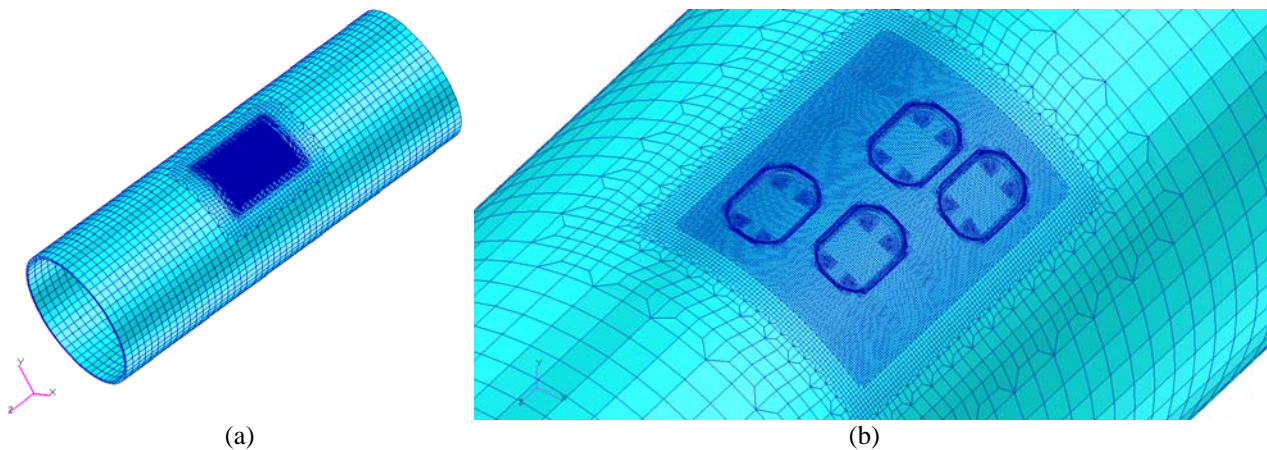


Figure 6: Model after the complete process: (a) pipe model and (b) transitions region.

### 3.3 General Algorithm

The computational implementation for the generation of pipes with defects at arbitrary positions follows the steps described on Table 1, with the main aspects of the implementation described in the previous sections.

Table 1: Algorithm for generation of pipelines with “ $n$ ” defects in arbitrary location.

- |        |   |
|--------|---|
| 1.     | Preprocessing – Generation of the front and back intersection matrices ( $M_{if}$ e $M_{ib}$ ) and the front and back intersection vectors ( $V_{if}$ e $V_{ib}$ ). |
| 2.     | Start of loop for $n$ defects   |
| 2.1.   | Start of frontal connections loop   |
| 2.1.1. | Check whether the defect number to be connected is lower than the current defect number.  |
| 2.1.2. | Check the preexisting groups (nodes) neighbors to the connection.   |
| 2.1.3. | Extract the required nodes from the boundary of the neighboring groups.   |
| 2.1.4. | Check mode of interaction (Motta et al, 2008).  |
| 2.1.5. | Generate solids and meshes for the connections.   |
| 2.2.   | End of frontal connections loop.  |
| 2.3.   | Start of back connections loop.   |
| 2.3.1. | Repeat steps 2.1.1 to 2.1.5.  |
| 2.4.   | End of back connections loop.   |
| 3.     | End of loop for $n$ defects.  |
| 4.     | Generate the remaining region.  |

#### 4. BOUNDARY CONDITIONS AND MATERIAL PROPERTIES

Appropriate boundary conditions and loads are automatically applied. The internal pressure is incrementally applied to the internal surfaces of the model and longitudinal forces due to the internal pressure are simultaneously applied to the pipe wall at the cut-off boundary of the models. The ANSYS program (ANSYS, 2004) was employed to perform the FE analyses which accounted for geometrical and physical nonlinearities.

The numerical results obtained here with the automatically generated models, are compared with results in literature (Benjamin et al, 2005; Benjamin et al, 2006a) and (Andrade et al, 2006). The pipelines considered in the cited works are made of API 5L 80X steel. The material properties used in the FEM analyses assume a rate-independent plasticity model using the von Mises yield criterion and adopt an isotropic hardening rule.

The values of Young modulus and Poisson's ratio used are, respectively: 200,000.0MPa and 0.3. The yield stress adopted is 534.1MPa and the true ultimate tensile stress is 718.2MPa the true stress-strain curve remains constant (converges) for a strain greater or equal to 0.15 and the constant von Mises stress of 754.2MPa. The failure criteria adopted here, and in the literature in which the FEM analyses was considered, assumes that failure occurs when the von Mises stress along all wall thickness elements (in radial direction) reaches the true ultimate stress value, 718.2MPa. All tubular specimens have nominal outside diameter of 457.2 mm (18 inch) and a nominal wall thickness of 7.93 mm (0.312 inch).

#### 5. APPLICATIONS

To validate the automatic procedure and the FE models here presented, the FP obtained with the automatically generated models is compared with experimental results obtained by burst tests (Benjamin et al, 2005; Benjamin et al, 2006a) and numerical results obtained by manually generated models (Andrade, et al 2006).

In Andrade et al (2006) six specimens are modeled computationally and the FP obtained by FEM analyses is compared with laboratory burst test from another work by Benjamin et al (2005), where specimens with idealized defects were manufactured. Three of these specimens were considered here, namely IDTS 5, IDTS 6 and IDTS 7. Due to symmetry, only one half or one quarter of the pipe was manually modeled in the referred paper (Andrade et al 2006), but automatic procedure does not yet implements symmetry and full FE models were generated.

In Benjamin et al (2006a) a continuity of the work in (Benjamin et al, 2005) is presented, in which burst test in five different manufactured specimens is carried out and the FP experimentally obtained are used to compare with semi-empirical assessment methods. Two of these five specimens are analyzed here, namely IDTS 9 and IDTS 11.

The failure pressures measured in the laboratory tests of the tubular specimens were compared with those predicted by four assessment methods (Benjamin et al 2007), namely, the American Society of Mechanical Engineers (ASME) B31G method, [BS7910, 1999] the Det Norske Veritas (DNV) RP-F101 [ DNV,1999] the RSTRENG effective area method [ KIEFNER and VIETH 1990] and a recently developed method called mixed type of interaction method (MTI) (Benjamin and Cunha 2006b).

Assessment methods, traditionally, are performed after using an interaction rule. Interaction rules for corrosion defects are in general expressed in terms of the spacing between two individual defects, the defects of all specimens consider are classified as interacting defects (cluster). Thus, the assessments methods assume the pipeline containing a single defect (with constant or complex shape).



Figures 7 to 11 illustrate the idealized manufactured defects used in burst tests of the five specimens considered here, the sketch of the defects dimensions and configurations and the respective FE models automatically generated by the PIPEFLAW program. The good quality of the automatic generated meshes is clear. The maximum time required to generate a single model was about five minutes.

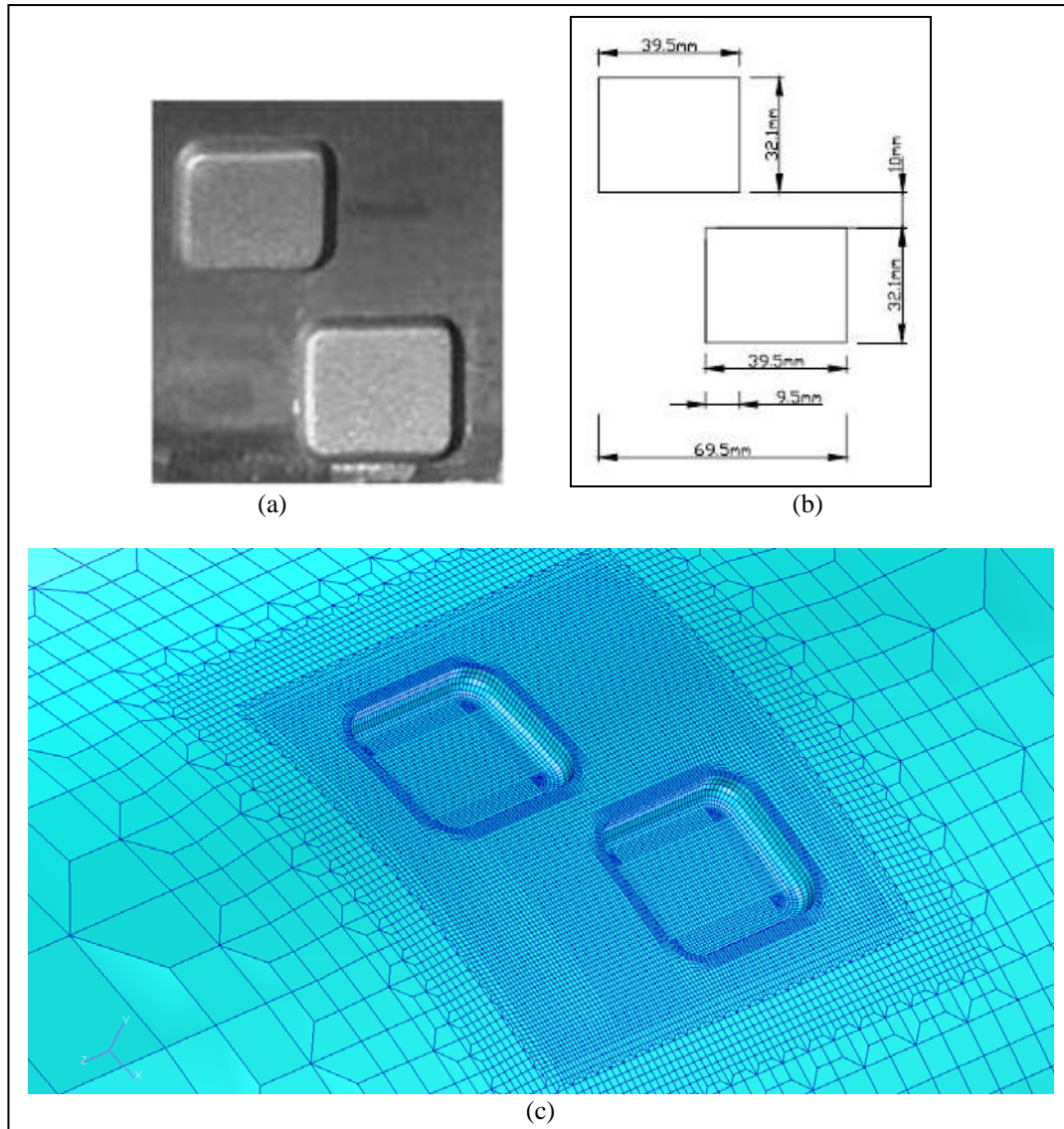


Figure 7: Specimen IDTS 5: (a) the manufactured defects, (b) the sketch of the defects dimensions and configurations and (c) the FE model automatically generated by the PIPEFLAW program.

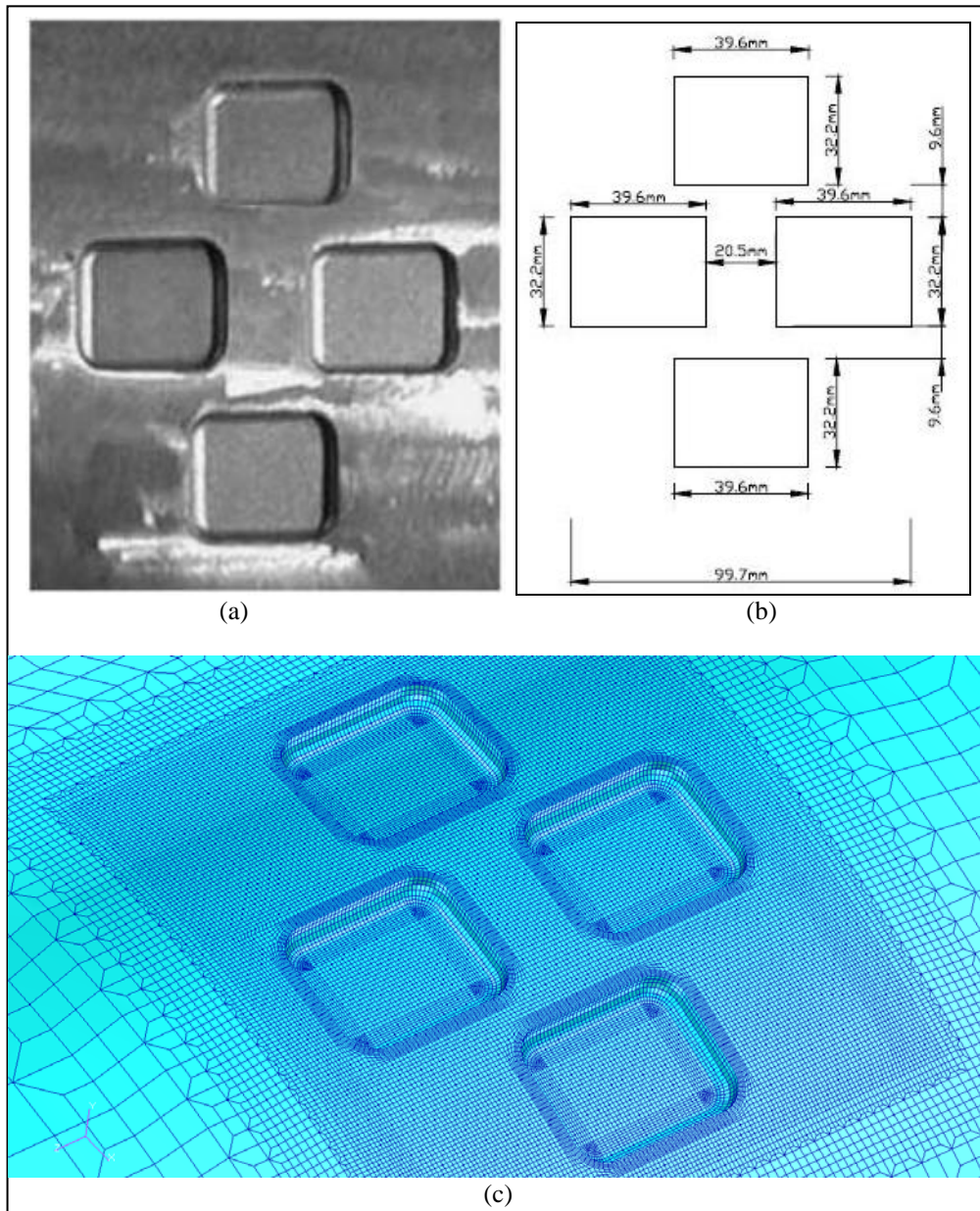


Figure 8: Specimen IDTS 6: (a) the manufactured defects, (b) the sketch of the defects dimensions and configurations and (c) the FE model automatically generated by the PIPEFLAW program.

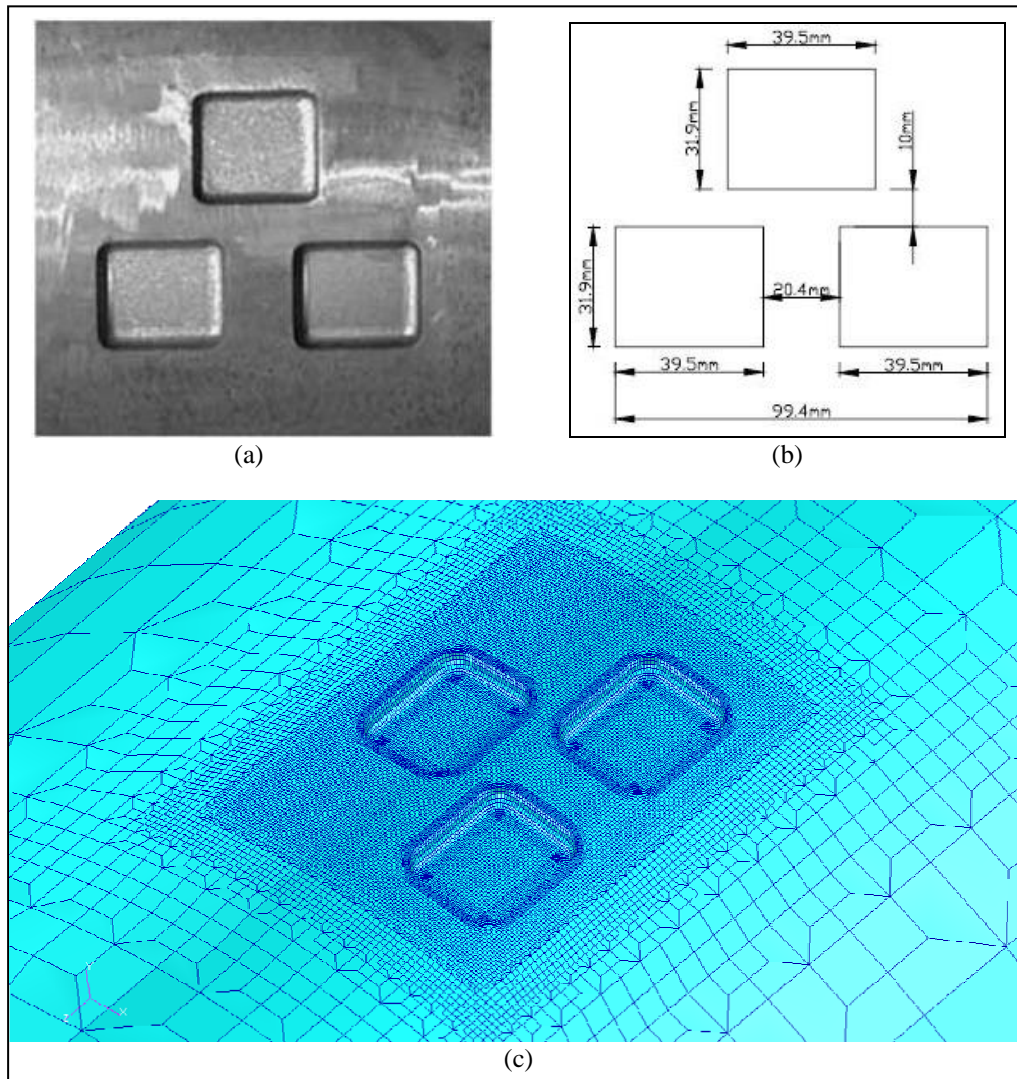


Figure 9: Specimen IDTS 7: (a) the manufactured defects, (b) the sketch of the defects dimensions and configurations and (c) the FE model automatically generated by the PIPEFLAW program.

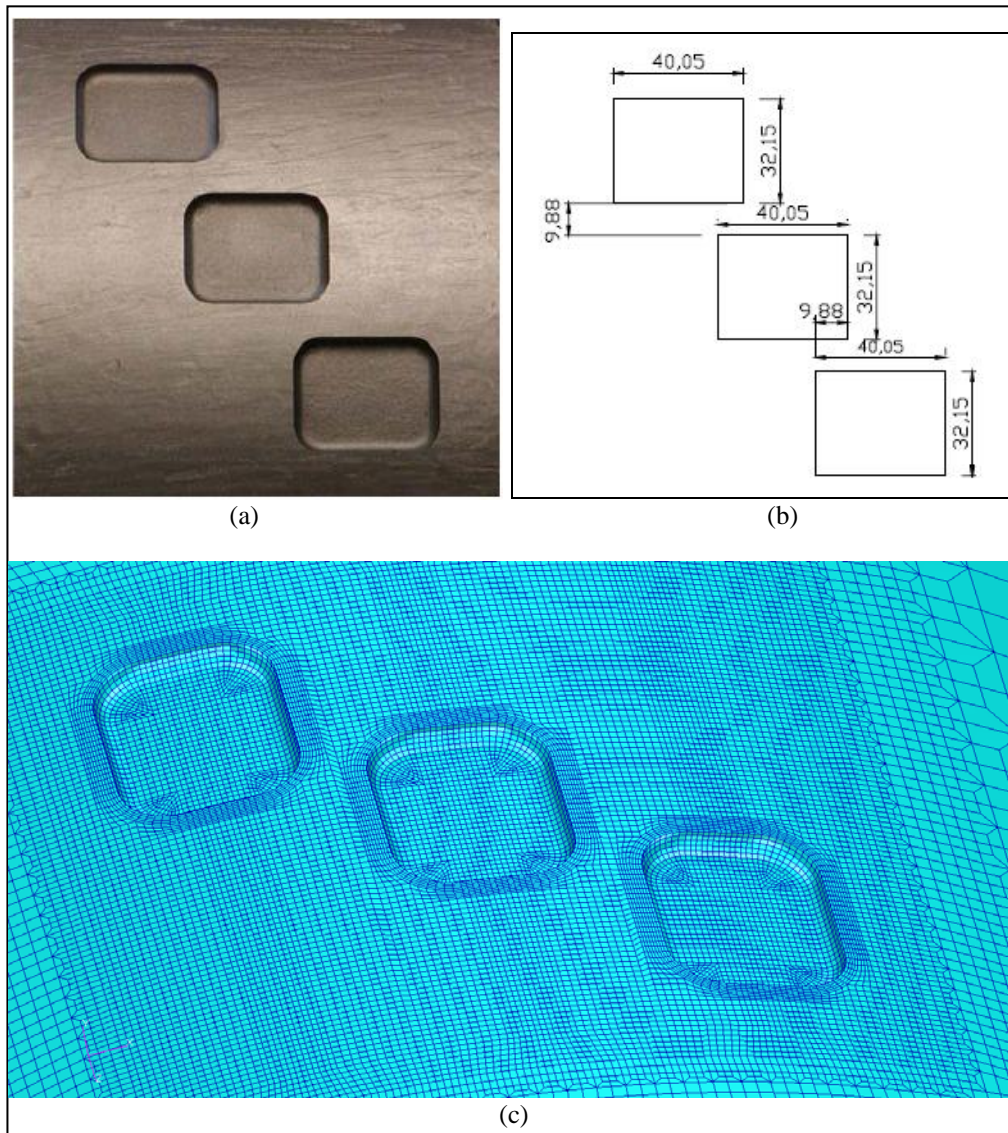


Figure 10: Specimen IDTS 9: (a) the manufactured defects, (b) the sketch of the defects dimensions and configurations and (c) the FE model automatically generated by the PIPEFLAW program.

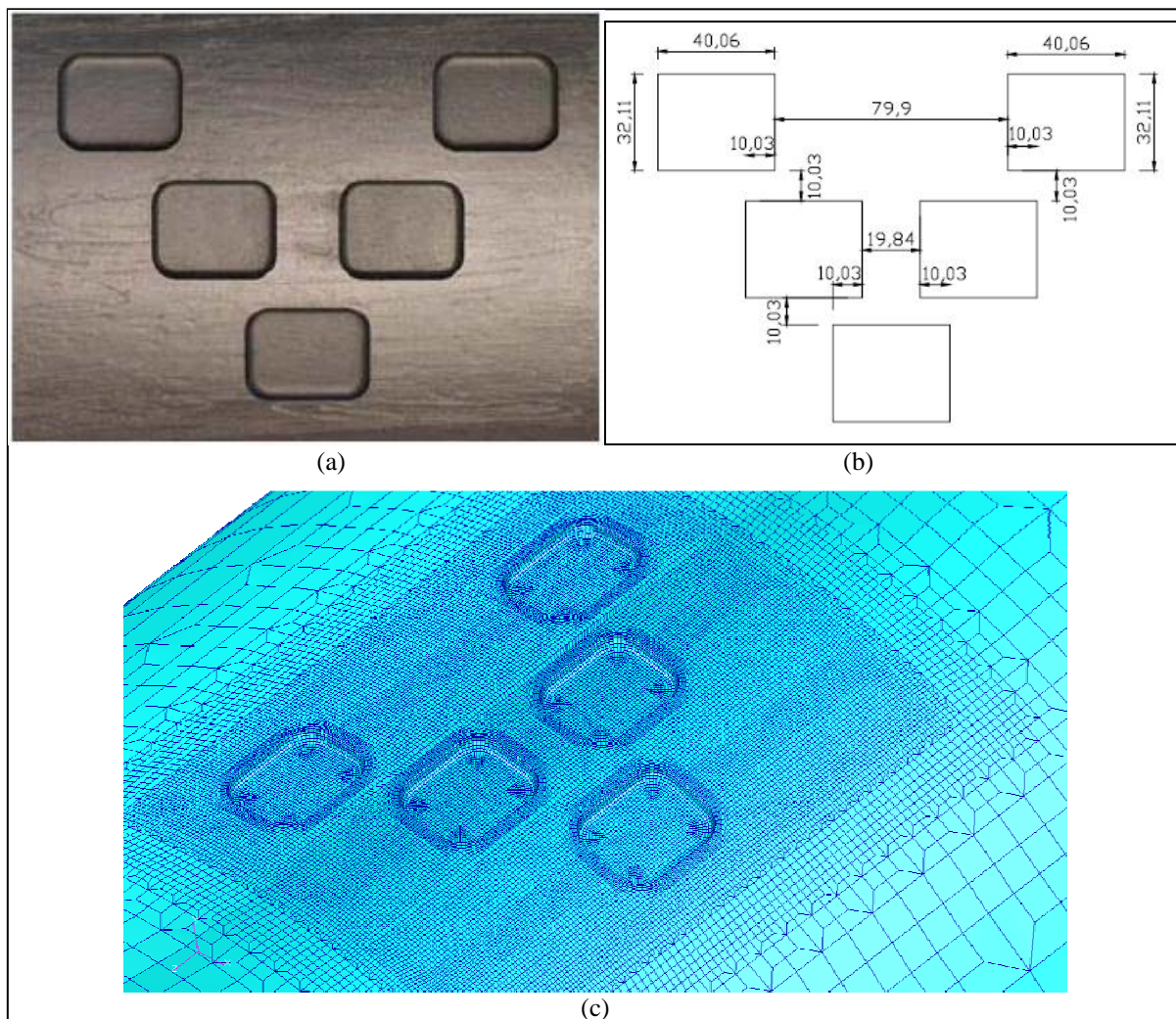


Figure 11: Specimen IDTS 11: (a) the manufactured defects, (b) the sketch of the defects dimensions and configurations and (c) the FE model automatically generated by the PIPEFLAW program.

Table 2 and Figure 12 present the summary of the FP obtained considering the following approaches: experimentally (by burst test) (Benjamin et al, 2005; Benjamin et al, 2006a), numerically through models generated manually (Andrade et al, 2006), numerically through automatic generated models by PIPEFLAW and FP predicted by four semi-empirical assessments methods, namely, the ASME B31G method, the DNV RP-F101 method for single defects (part B), the RSTRENG effective area method, and the MTI method (Benjamin and Cunha 2006b).

As can be observed, the FP values obtained by both FE models (manual and automatic) are in agreement and are slightly different of the results obtained by the experimental tests. Except for the MTI, all semi-empirical methods results in very conservative FP values, the MTI method obtained low error results, however they are non conservative.

Table 2 - Summary of the FP results obtained (MPa).

	Burst test	Manual FE	PIPEFLAW	ASME B31 G	DNV RP-F101	RSTRENG	MTI
IDTS 5	20,87*	20,08***	20,24	18,80	18,70	15,82	21,96
IDTS 6	18,66*	19,19***	19,15	17,34	16,20	13,55	19,03
IDTS 7	18,77*	19,09***	19,18	17,53	16,59	13,95	19,26
IDTS 9	23,06**	-	22,00	18,04	20,79	16,89	24,50
IDTS 11	21,26**	-	21,49	16,58	18,52	15,21	22,27

\* Benjamin et al (2005); \*\* Benjamin et al (2006a); \*\*\* Andrade et al (2006)

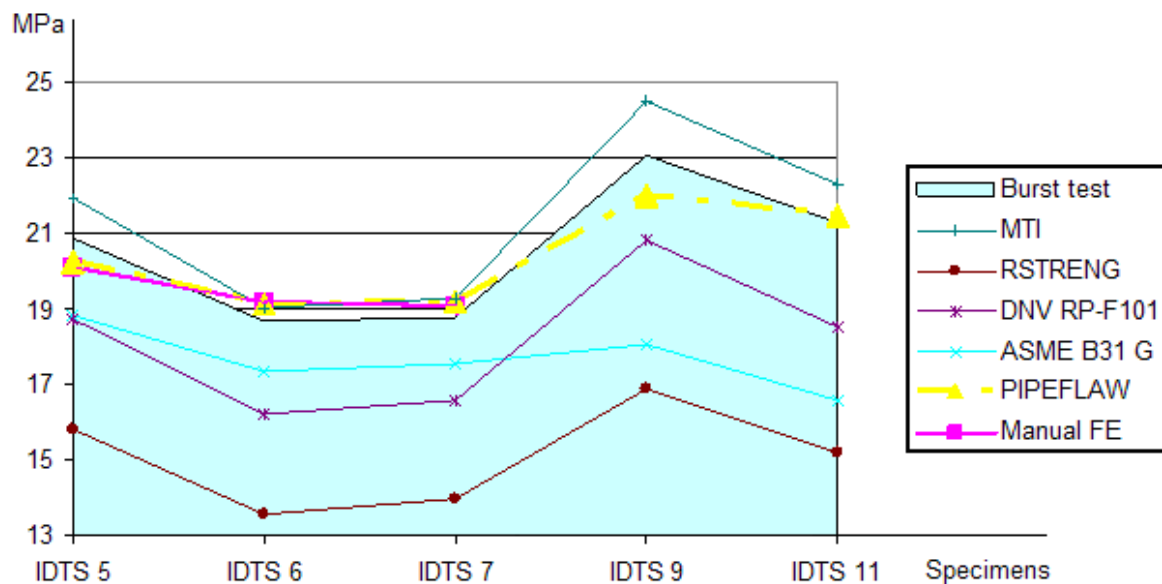
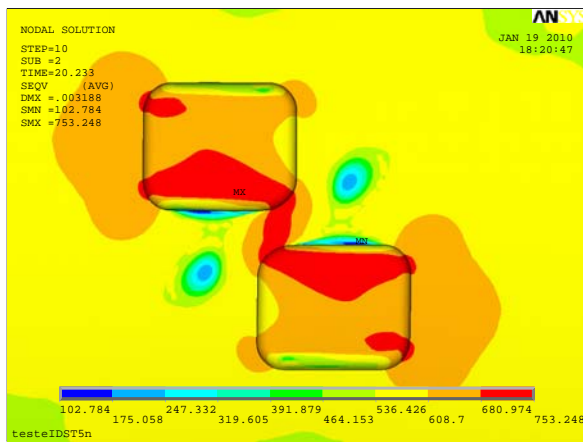


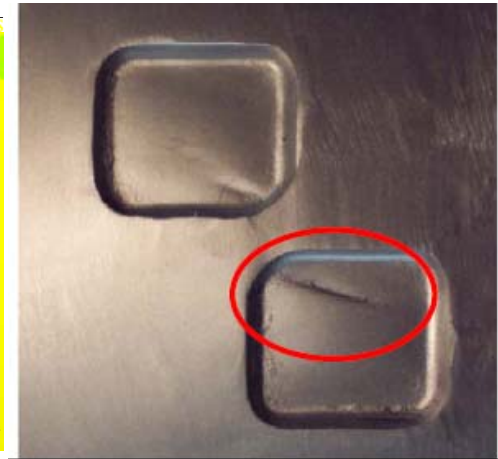
Figure 12: Summary of the FP results obtained.

Figures 13 to 16 illustrate the final result of the non-linear FE analyses of the specimens considering the models and boundary condition automatic generated by the PIPEFLAW program and the manufactured defects after the burst tests. For specimens IDTS 5, IDTS 6 and IDTS 7 Figures 13, 14 and 15, respectively, the result of the non-linear FE analyses considering the models and boundary condition generated manually (Andrade et al 2006) are given.

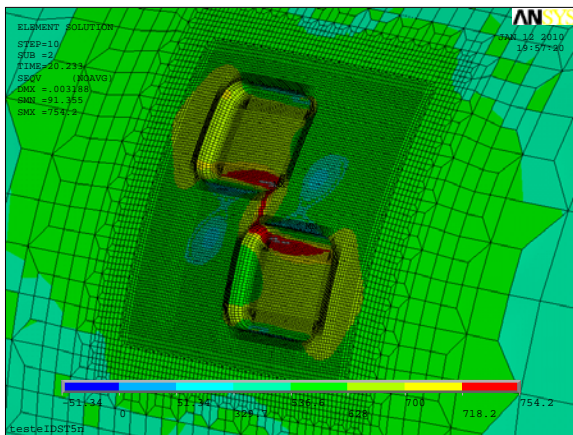
The results obtained by PIPEFLAW FE models capture the correct failure region, as do the manually generated FE models. The von Mises stress contours, obtained by both FE models (manual and automatic), are in good agreement.



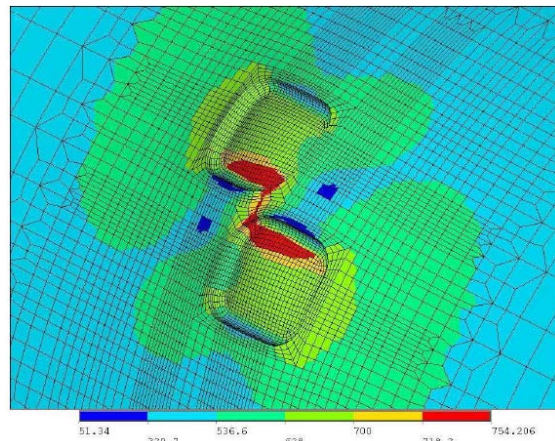
(a)



(b)

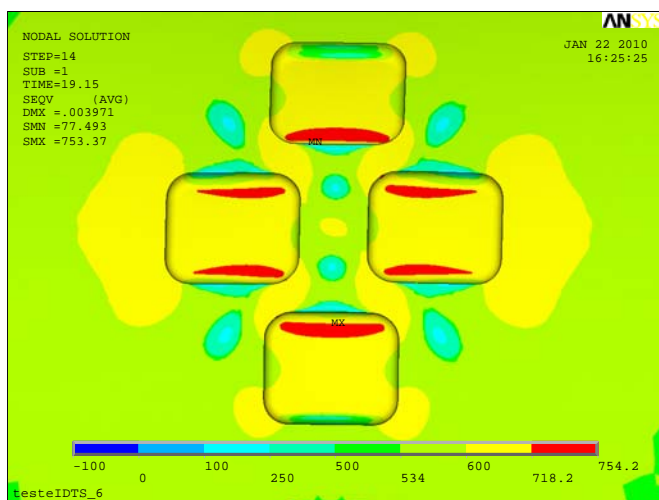


(c)



(d)

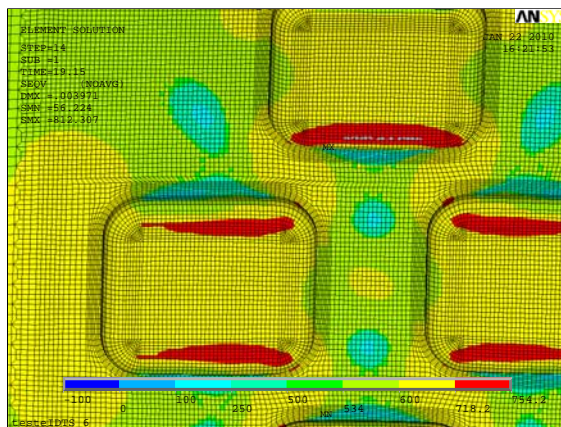
Figure 13: Results for the IDST 5 specimen applying the failure pressure: (a) von Mises contour for the FE model automatic generated by the PIPEFLAW program without mesh, (b) the real burst manufactured, (c) von Mises contour for the FE model automatic generated by the PIPEFLAW program with mesh and (d) von Mises contour for the FE models generated manually (Andrade et al 2006).



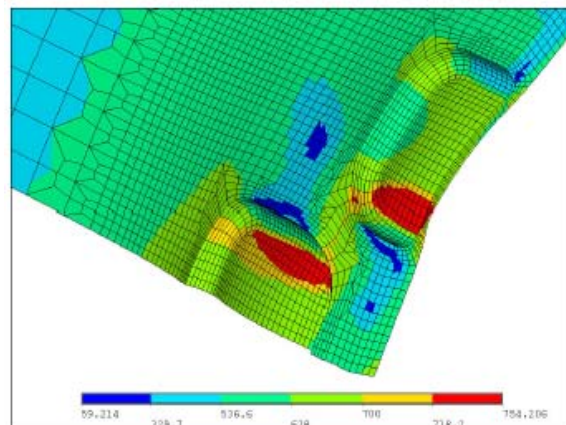
(a)



(b)



(c)



(d)

Figure 14: Results for the IDST 6 specimen applying the failure pressure: (a) von Mises contour for the FE model automatic generated by the PIPEFLAW program without mesh, (b) the real burst manufactured, (c) von Mises contour for the FE model automatic generated by the PIPEFLAW program with mesh and (d) von Mises contour for the FE models generated manually (Andrade et al 2006).



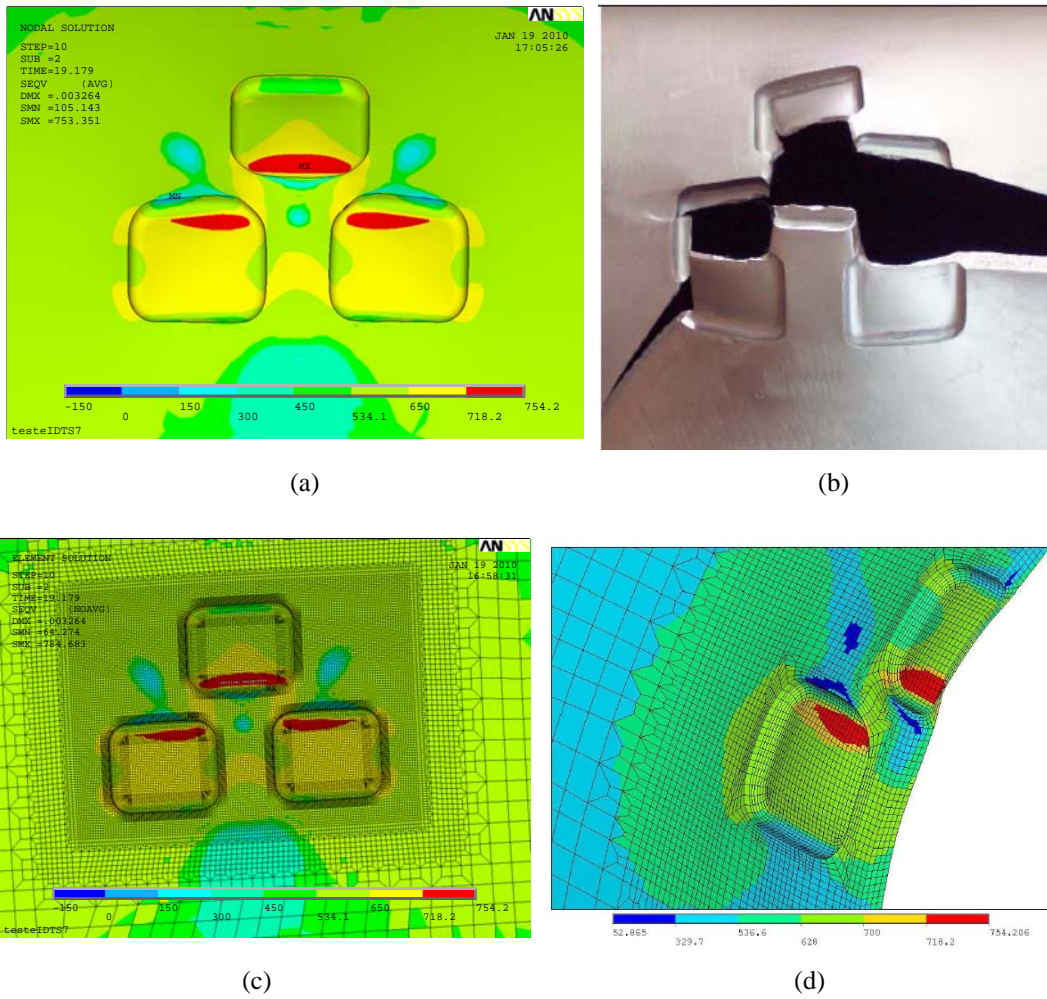


Figure 15: Results for the IDST 7 specimen applying the failure pressure: (a) von Mises contour for the FE model automatic generated by the PIPEFLAW program without mesh, (b) the real burst manufactured, (c) von Mises contour for the FE model automatic generated by the PIPEFLAW program with mesh and (d) von Mises contour for the FE models generated manually (Andrade et al 2006).

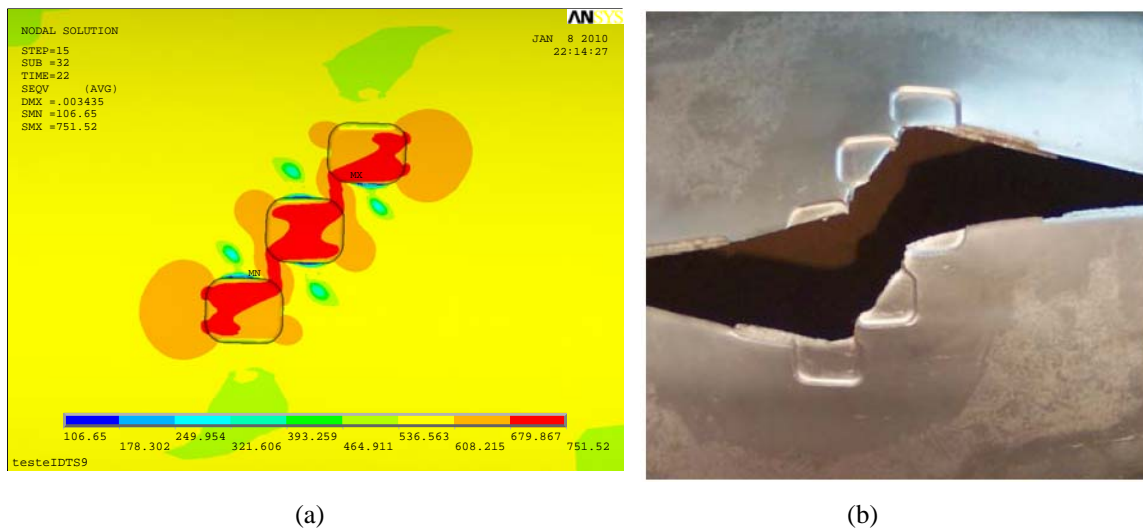


Figure 16: Results for the IDST 9 specimen applying the failure pressure: (a) von Mises contour for the FE model automatic generated by the PIPEFLAW program without mesh, (b) the real burst manufactured.

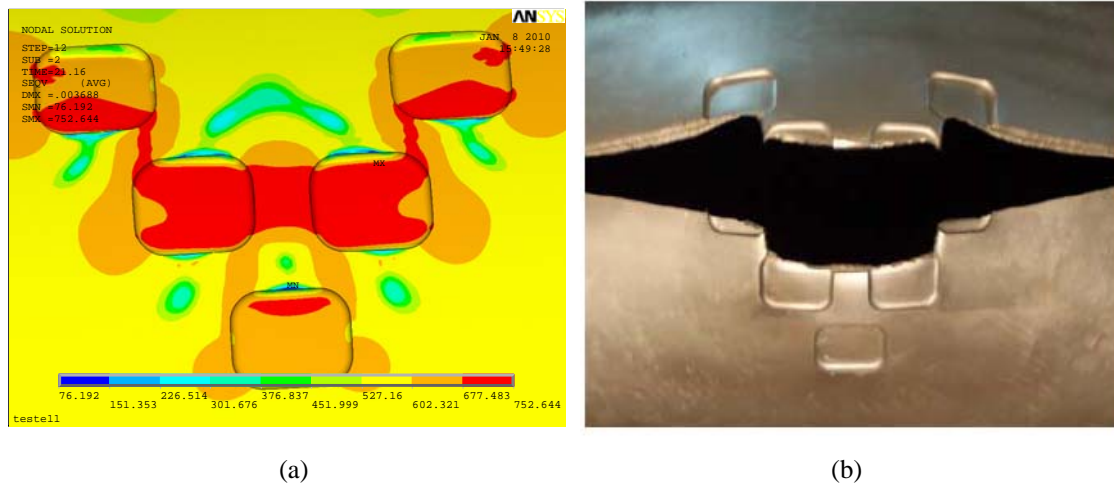


Figure 17: Results for the IDST 11 specimen applying the failure pressure: (a) von Mises contour for the FE model automatic generated by the PIPEFLAW program without mesh, (b) the real burst manufactured.

## 5. CONCLUSIONS

A new procedure to automatic generation of FE pipelines models with corrosion defects in arbitrary positions, located on the internal or the external pipe surface, considering the mesh transition requirements used by CENPES/PETROBRAS was presented. This additional procedure was incorporated in PIPEFLAW program. Some model limitations were eliminated, mainly related to the spacing between adjacent defects. The new procedure automatically generates FE models of pipelines with very close corrosion defects arbitrarily located in the pipe

The PIPEFLAW program has proven to be an excellent tool to create rapidly and reliably FE models of pipes with multiple corrosion defects in arbitrary locations. With the use of PIPEFLAW tools one can accelerate the process of modeling and simplify the execution of parametric studies. In the present work the behavior of pipelines subjected to multiple defects was investigated.

ANSYS software was used for physical and geometrical non-linear analysis of the models to obtain the failure pressure (FP) value. The FP obtained with the automatically generated models, was compared with experimental results obtained by burst tests (Benjamin et al, 2005; Benjamin et al, 2006a), numerical results obtained by manually generated models (Andrade et al, 2006) and FP predicted by classic assessment methods.

The obtained results validate the automatic procedure and the FE models built. This work allows the application of the FEM to predict FP in practice and, furthermore, in the investigation of assessments methods, as well as in the conception of new ones.

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