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Development of a Validated Numerical Model of an Unreinforced T-section Pipe for Large Dams

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Abstract

This paper reports on the development of a validated numerical model (using 3-D finite element method (FEM)) of an unreinforced T-section pipe. Pipe profiling severely compromises the localized performance of the T-section pipe. The main objective was to develop a less conservative tool to investigate the key factors that influence failure in T-section pipes. Strain gauges were mounted on the T-section to capture the induced strains as the pressure was gradually increased until the pipe burst. The executed FEM analysis provided comparable results to the experimental measurements which provided a cost effective tool to validate the numerical model. This result allows for better placement of branch piece reinforcements based on experimentally obtained results. The developed tool c be used to optimize the design and sizing of reinforcing crotch plates.

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Keywords: branch piece reinforcements, FEM, Ureinforced T-section

1. Introduction

Branch piece reinforcements have been successfully used to reinforce pipe junctions in pipe networks that serve as conduits for transporting water for water reticulation systems [1]. In order to supply water to a desired location, the direction of flow may have to be changed. This is usually achieved by joints of various types such as Y, T, and wweep T or even cross configuration junctions. These may be used to change the direction of flow depending on the

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particular application [1]. Usually, on an inflow through large diameter pipes, a hole is cut in the barrel (main pipe) in order to fit the branch into the barrel to allow for change in the flow direction. A branch piece reinforcement which is usually a flat or curved plate is utilized in between the branch and the barrel known as the junction. This is done to hold the curved part of the tube, which is inadequately constrained due to the hole cut in it. As a result of this arrangement, internal pressure induced deformations lead to longitudinal and hoop stresses tending to flatten the pipe leading to localized bending and buckling. This may lead to T-junction failure. Therefore, reinforcement of the pipe junction ensures that the whole pipe configuration is safe and failure is thus negated [2].

The first concepts of branch piece reinforcements were founded by the Sulzer Brothers in 1928 as stated by Blair [2]. The last known work was done in 1946 [2]. The American Water Works Association (AWWA) has also developed techniques for the design of branch piece reinforcements which are very conservative with respect to profiles [3]. Plate thicknesses for reinforcements were by default selected to be 25 mm (1 inch) by first iterative process. This was unnecessarily too thick for some applications and the plate depth is also generally oversized [3].

A challenge has, therefore, been identified to optimize the manner in which branch piece reinforcements are developed. By developing a validated numerical model of an unreinforced T-section, branch piece reinforcement profiles can be analyzed and optimized. Full scale prototype testing is very expensive with respect to material, testing equipment and transportation. Furthermore, it is not realistic to conduct tests on every possible design solution developed. Therefore, numerical modeling may provide a more cost effective alternative. By developing a numerical model of an unreinforced branch pipe it will assist with accurately analyzing and interpreting most possible failure modes and critically loaded areas on the pipe joint. The numerical model can then be used as a tool to develop new designs and enable a cost effective solution for future use and investigation.

2. Research Methodology

2.1 Background

The aim of the experiment was to measure the strains at specific locations of the T-section pipe as a function of the internal pressure. The material used in this investigation was a low carbon mild steel (i.e. 50025/EN 10025-2 S355JR+AR) which was supplied by Aveng in plate form with dimensions 1200 x 2400 x 3mm for the main and barrel pipes; 10000 x 1200 x 30 mm for the flanges. The chemical composition of the material and the corresponding mechanical properties as per manufacturer certificate are given in Table 1 and Table 2 respectively.

Table 1. Composition of low carbon mild steel used in this investigation

Elements	%	Elements	%	Elements	%
C	0.1490	Ni	0.0690	N	0.0094
MO	0.0000	S	0.0021	TI	0.0010
MN	1.4680	CR	0.0210	AL	0.0310
V	0.0540	SI	0.4600	B	0.0002
P	0.0090	NB	0.0010	CU	0.0610

Table 2. Mechanical properties of the low carbon steel used in this investigation

Property	Value
Test Piece Position & condition	TX 10
Yield Strength 0.2% (MPa)	418
Tensile Strength (MPa)	603
Yield / Tensile Ratio	0.69
EL 5.65*/A (%)	25

2.1 Specimen Design & Manufacture

Thin wall pressure vessel theory was assumed for the design adopted from Rogers [4]. The geometrical dimensions of the test specimen were in accordance to a similar test executed by the Council for Scientific and

Industrial Research (CSIR) although their specimen was a Y-section pipe [5]. The design of flanges and all welding analysis were executed according to the Barlow formula. This was achieved by multiplying the formula by the pressure-to-strength ratio, the yield and burst pressure which were calculated to be 4.35 & 6.29 MPa, respectively [6, 7]. Due to limitations of the pump capabilities, it was necessary to design the pipe as thin as possible at the same time providing enough weld material for a suitable attachment to the flanges to negate failure of the welds and allow pipe yielding in order to identify the areas of failure incidence. Therefore, a pipe thickness of 3 mm was selected. The test specimen was manufactured by the Department of Water & Sanitation's construction hub i.e. Construction Central at Jan Kempdorp utilizing pressure vessel principles. The flat plate was first laser cut to the stipulated profiles then cold rolled and arc welded using a 3.125 mm electrode. Flanges, gussets, inlet and outlet pipes were attached by arc welding. The manufactured specimen is shown in Fig. 1.

Fig. 1. Manufactured test specimen

2.2 Equipment Used for Testing

Pressure tests were executed using a 60 bar positive displacement pump. The applied pressure was adjusted manually at 0.5 MPa increments. Water flow to the inlet of the specimen was controlled using a 6 bar ball valve as shown in Fig. 2. The 350 Ohm HBM unidirectional strain gauges were installed and connected in a quarter Wheatstone bridge configuration to respond to pipe deformations as explained by National Instruments and Electronics hub [8, 9]. A gauge factor of 2.09 was used. The strain responses were captured using Compact DAQ data logger connected to a laptop utilising a pre-installed Signal Express software. This was done in conjunction with strain calculation theory [11, 12].

Fig. 2. 80NB intake ball valve

2.3 Testing procedure

Strain gauges were installed at identified stress concentration areas based on preliminary finite element analysis as shown in Fig. 3 (a) and (b). The strain gauges were then connected to the National Instruments Compact DAQ data logger using a NI 9219 strain measurement module. Prior to data logging, water is pumped into the test specimen via the 80 NB pipe (inlet pipe). At this stage the 80 NB ball valve and air outlet are opened as shown in Fig. 4(a). As soon as water begins to exit from the air outlet, the outlet is blanked off (via a blank flange). This is an indication that the specimen is full and ready for pressurization. Water is then pumped into the specimen at 0.5 MPa increments and the pressure and strain readings are recorded. The process is continued until pipe failure as shown in Fig. 4(b).

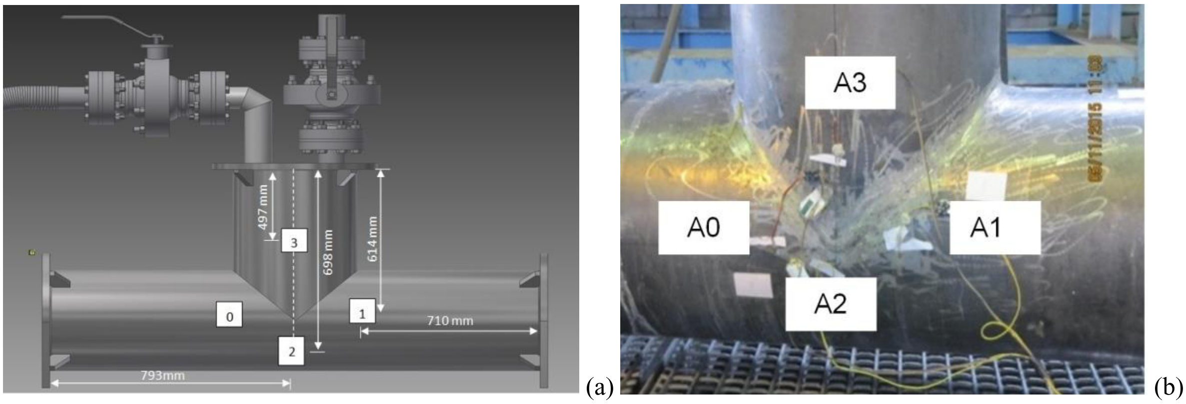

Fig. 3. (a) Parasolid model illustrating strain gauge installation positions and (b) Actual strain gauge installation positions

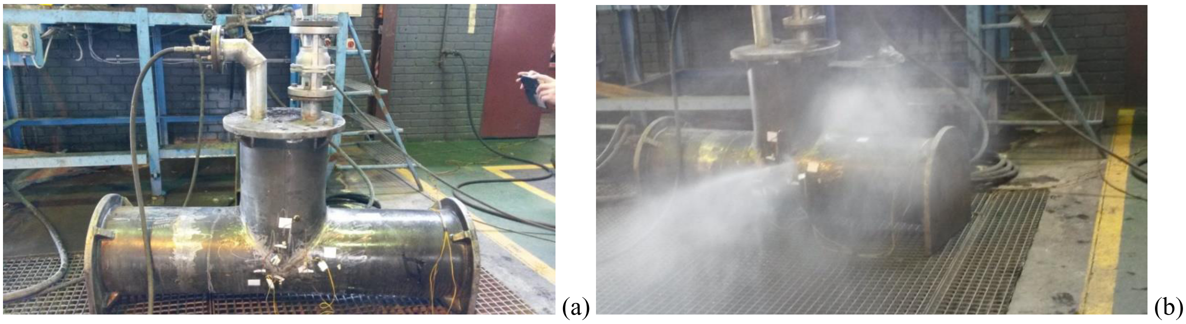

Fig. 4: (a) Water filling and air release installation and (b) Pipe failure

3. Experimental results

The pressure vs. strain responses of three of the strain gauges i.e. A1-A3 are shown in Fig. 5. One strain gauge (i.e. A0) did not generate a response. This is probably due to a short circuit or damage to the strain gauge. Nevertheless, this did not affect the validity of the test as strain gauge A1 would generate the same responses as strain gauge A0 since they were symmetrically located about the y axis (vertical/upwards direction). The measured strain values shown in Fig. 5 exhibit expected behaviour with pressure. As the internal pressure is increased, the strains are expected to increase linearly with increasing pressure. At some point prior to failure, non-linear behaviour is expected. This leads to local strains attaining maximum values if the strain gauges do not fail. This is shown for gauge A2 at pressures of 5.5 and 6 MPa.

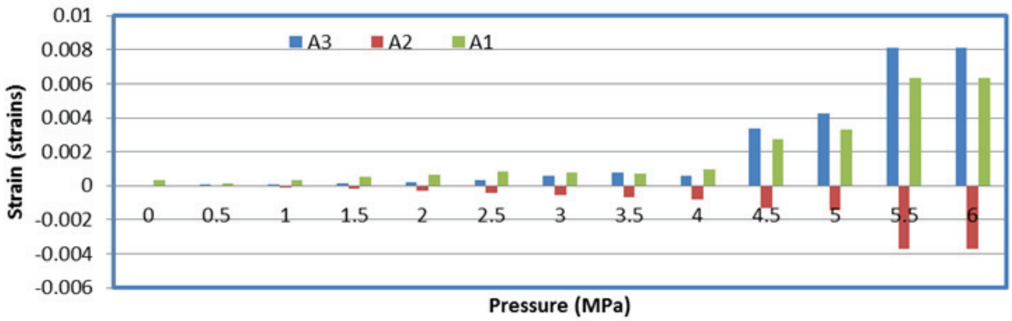

Fig. 5. Pressure vs. strain response of test specimen

4. Numerical model

A finite element based numerical model of the T-section prior to reinforcement was developed using commercial software MSC Nastran [13]. The aim of the modelling was to develop a finite element based tool that can be used to study the behaviour of the T-section pipe prior to and after reinforcement with crotch plates. The material was assumed to be linear elastic for validation purposes. The material properties used are given in Table 2. In short, the elastic modulus was set at 208 GPa with a Poisson's ratio of 0.3 and density of 7850 kg/m^3.

4.1 Modelling geometry and boundary conditions

The geometry of the model was developed from the design parameters presented in Fig. 1. A full 3 D model was developed from the simplified geometry in Autodesk Inventor software. Fig. 6 shows the boundary conditions applied to the model. The left and right flanges of the test specimen were fixed using multiple point constraint (MPC) rigid body elements (RBE) 2, constraining the left flange in all directions except rotation about the z direction lateral to the length of the pipe and constraining the right flange with respect to vertical displacement similar to the research work done by Proctor [18].The solid model was then converted into mid plane surfaces for 2 D meshing in MSC Nastran according to analysis of thin shell cylinders [13]. All major pre- and post-processing were executed in MSC Patran [14, 15]. Further additional methodologies used were for general geometry modelling [16, 17].

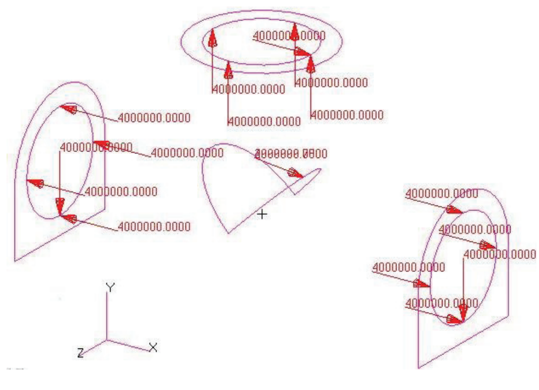

Fig. 6: Applied boundary conditions

Shell elements were used for the analysis and the model was meshed with quad 4 elements utilizing a paver mesher. A global edge length i.e. mesh size of 0.002 m was selected. The loading was applied as internal surface pressure (See Fig. 6). Since the material model was assumed to be linear elastic, the pressure was therefore limited to 4 MPa as the Barlow formula predicted a yield pressure of 4.35 MPa for this pipe configuration.

4.2 Model/simulation results

The distribution of von Mises stresses for an internal pressure of 2 MPa are shown in Fig. 7. This shows the general nature of the stress field experienced by the component. It is clear from Fig. 7 that the junction between the barrel and the T-section is the most critically stressed. This shows the need for reinforcing this area to prevent local buckling. From this stress field, the strains at the strain gauge positions and directions are then extracted. Strain predictions for strain gauge A3 were accurate to within 5% of experimentally measured values. For a pressure of 2.5 MPa, the numerical model predicted 0.00034919$\mu\varepsilon$ for gauge A3 compared to 0.000345$\mu\varepsilon$ experimentally. Strain gauge A1 displayed good responses as well with only an average percentage error of 17.59%. For a pressure of 3.0 MPa, the numerical model predicted 0.000849$\mu\varepsilon$ for gauge A1 compared to 0.000783$\mu\varepsilon$ experimentally. Strain gauge A2 displayed the largest errors from the other two strain gauges. This is probably due to the location of this gauge, as this gauge is placed below the centre line of the main pipe whereas the other two gauges where placed on the horizontal axial plane of the pipe.

The results of the strain responses for both numerical prediction and experiment are summarised in Table 3. The error margins obtained are within experimental error and are therefore acceptable. The numerical model can therefore be considered to be accurate enough to predict the behaviour of this T-section. Fig. 8, shows the comparison of the experimental data with the numerical predictions as a function of applied pressure.

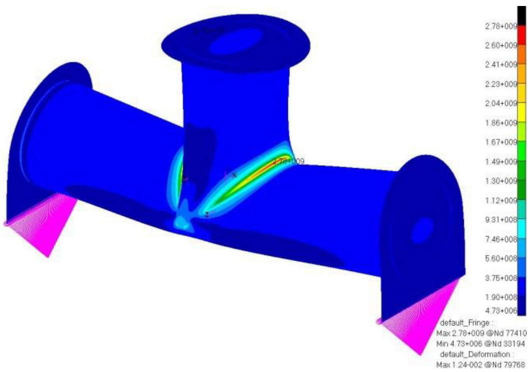

Fig. 7: von Mises stress distributions

Table 3. Summary of experimental test results vs. Numerical model results

Pressure (MPa)	A3 Experimental	A3 Numerical Model	A2 Experimental	A2 Numerical Model	A1 Experimental	A1 Numerical Model
0.5	1.98E-05	-6.97E-05	-3.20E-05	1.03E-04	0.000157	0.000142
1	7.08E-05	-0.00049	-9.93E-05	0.000723	0.000337	0.000995
1.5	0.000144	-0.00021	-0.0002	0.000311	0.00052	0.000423
2	0.000208	-0.00027	-0.00029	0.000415	0.000646	0.000564
2.5	0.000345	-0.00035	-0.00044	0.000513	0.000823	0.00072
3	0.000579	-0.00042	-0.00053	0.000616	0.000783	0.000849
3.5	0.000764	-0.00049	-0.00065	0.000734	0.000727	0.000968
4	0.000599	-0.00056	-0.00083	0.00083	0.000945	0.001137

	3.41E-04	-3.58E-04	-3.84E-04	0.000531	0.000617	0.0007255
Error (%)	5%		38.28 %		17.59%	

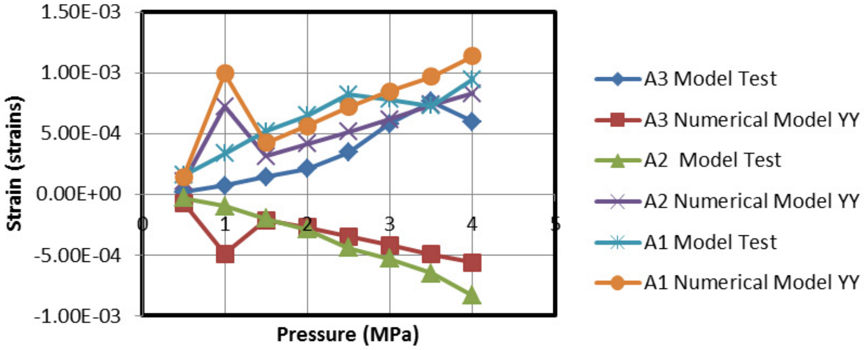

Fig. 8. Accuracy of Model Test vs. Numerical Model

5. Conclusions

A T-section pipe was fabricated from mild steel plate and subjected to destructive testing using pressurised water. Strains were measured during the tests and used to validate a numerical model that was generated using the finite element commercial code MSC. Nastran. From the results obtained, the following conclusions can be made:

- The strain responses of strain gauge A3 on the numerical model recorded strains which agreed well with the numerical model with a 5% error. This is acceptable and validates the developed numerical model.
- Failure during tests occurred along the welded joint between the main and branch pipes. This was in agreement with numerical predictions.
- The numerical model was therefore found to be an accurate tool for predicting T-junction behaviour and can therefore be applied to the analysis of T-junction reinforcement crotch plates.
- The numerical model can now be considered as being validated as the errors are appreciably low and branch piece reinforcements can now be developed with the understanding that this numerical model yields good results.

6. Recommendations

It is therefore recommended that future work be focussed on capturing non-linear responses of the strain field. This will require experimental determination of the actual stress-strain response of the material to be included in the numerical model. Methods of accurately locating the position of strain gauges should be developed to improve accuracy. Recommended mathematical formulae and techniques to develop the branch piece reinforcements shall be in accordance to methods of calculating defection on curved and elliptical structures.

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