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Analysis of Residual Stresses in Butt Welded Steel Pipe

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ABSTRACT

Due to non uniform temperature distribution during welding material close to weld joint is subjected to different rates of expansion and contraction. Due to this expansion and contraction phenomenon residual stresses are developed in the material near the weld joints. This welding residual stresses enhance occurrence of brittle structure, fatigue structural cracking and stress cracking. The primary area of component cracking in pipe system is at welded joint. One of the main causes of failure of pipe weldment is stress concentration cracking and this occurs due to residual stresses present in weld region therefore it is necessary to evaluate the magnitude and distribution of residual stresses in pipe weldment. In order to lower cracking probability residual stress distribution will be analysed using finite element method. The ANSYS model will be developed for FE analysis of welded section of the pipe and finally residual stresses will be measured experimentally by using techniques such as hole drilling technique.

Keywords— **residual stress, weld joint, pipe weldment**

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I.INTRODUCTION

Major construction, process, manufacturing, power generation and transport industries seek to underwrite safe reliable and economic use of structure and components that make up the profile of their plant. An essential input to achieve this is structural integrity assessment structural integrity assessment is an activity that draws together the individual fields of inspection and monitoring, mechanical and physical properties of materials welding technology structural analysis general engineering safety and economic assessment .The designer of structures and components follow guided interactive process directed to achieving a practical balance between structural capabilities and service requirements. Due to micro structural complexities and associated stresses weldments are required to assess. For structural integrity assessment it is necessary to have knowledge of both the primary stresses and secondary stresses in particular residual stresses.

Due to non uniform temperature distribution during welding, material close to weld joint is subjected to different rates of expansion and contraction. This develops three dimensional complex residual stresses in welded object. Welding residual stresses in welded structures are particularly affected by several parameters .in particular the structural and material factors and welding parameters. The structural factor includes the type of geometry, sizes, type of weld joints and weld groove shape. The material factor includes mechanical and physical properties of parent and filler materials. Welding process parameter includes type of process employed, current, welding voltage and arc travelling speed etc. Welding residual stresses enhance occurrence of brittle fracture, fatigue, structural buckling, and stress cracking therefore correct estimation of magnitude and distribution of welding residual stresses and evaluation of their effect are important in structural integrity assessment of welded structure.

The primary area of component cracking in piping system is at welded joint .One of the main cause of failure of pipe weldment is stress concentration cracking and this occurs due to residual stresses present in weld region particularly if there are surface tensile stresses in regions. Therefore it is necessary to evaluate the magnitude and distribution of residual stresses and to explore whether the stresses are great enough to cause cracks. Therefore residual stresses in pipe to pipe weldment are going to analyse during this project.

1.1 PROBLEM STATEMENT

When two pipes are welded together undesired residual stresses and deformations are produced in the vicinity of weld region as a result of plastic deformation caused by non uniform thermal expansion and contraction in welding process .The presence of weld induced residual stresses can be a major concern in structural integrity assessment of weld parts. When combined with service loads welding residual stresses can reduce the fatigue life, accelerate growth rate of pre existing or service induced defects in pipe systems. Accurate estimation of weld induced residual stresses is therefore very crucial for production of an economic design and safety of structures. Therefore we have decided to study residual stresses in butt welded steel pipes in this project.

1.2 OBJECTIVES

1. To develop ANSYS models for FE analysis of welded section of pipe.
2. To procure material and test for validation.
3. To obtain residual axial stresses on outer surface at different positions from weld centerline.
4. To obtain residual hoop stresses on outer surface at different positions from weld centerline.
5. To identify the advantages or limitations of Computational results obtained from ANSYS.
6. To compare results obtained from ANSYS and experimental procedure.
7. To apply ANSYS model for different diameters of pipe.

1.3 METHODOLOGY

Steel pipes are widely used in various engineering applications like chemical industry sugar industry, paper industries, and process industries .When two pipes are welded together residual stresses are induced in weld region due to plastic deformation caused by non uniform thermal expansion and contraction. These residual stresses are going to be simulated by finite element software using ANSYS and we will also measure these residual stresses experimentally by technique like x ray measurement technique. Two pipes of outer diameter of 150mm and thickness of 7 mm will be butt welded using TIG welding. Automatic robotic welding will be used for welding purpose. For residual stress analysis measurement technique like x-ray measurement or hole drilling method will be used. We will also compute residual stresses at for different diameters of pipe. The measurement of the axial and hoop residual stresses at different location from centerline of weld will be done during this project.

ILITERATURE REVIEW

Sattari-Far, M.R.Farahani [1]

This paper consist of finite element technique to analyses the thermo mechanical behavior and residual stresses in butt welded pipes. The hole drilling method is used to measure the residual stresses in this paper. Two pipes with outer diameter of 320 mm thickness of 10 mm and length of 500 mm with v grooved edge are prepared. TIG welding with advanced control system is used for pipe welding. The hole drilling strain gauge method is uses for measuring residual stresses eleven points at outer surface of the pipe were made for stress measurement. These points are located on a straight line along the axial direction of the pipe. strain gauge of the rosette type were mounted on the pipe at the selected points to measure the released strain after drilling in the centre point of the gauge by very high speed drill. After measuring the strain in circumferential and axial direction the stresses are calculated from measured strains. In this paper 6mm thickness pipe is welded with 3 different groove shape the result of comparison between the axial residual stresses of three groove shapes at the inner and outer surfaces of the pipes it is observed that in general the weld groove shape in these 6mm pipes has no significant effect on the magnitude of hoop residual stresses. For 10 mm thick pipe weld groove has no significant effect on peak of hoop stresses at inner surface .but with x2 grooved shape significant increase in axial tensile stress on the inner surface of the pipe as compared with v and u grooved shape. The weld pass number has no significant effect on residual stress distribution in the outside surface of thin butt welded pipe. Hoop residual stress in inner surface of thin pipes significantly decreases when pass number increases.

Jie Xu , Xiaolei Jai , Yu Fan , Anmin Liu, Chonghao Zhang[2]

In this paper 3 D thermal mechanical finite element model is developed in order to accurately capture the 3D feature in residual stress and temperature distribution in circumferential butt welded steel pipe weld. In this paper carbon structural steel pipe with outer diameter of 50 mm thickness of 7 mm and length of 200mm is used .An axi-symmetric model which contain 1555 element and 3D model which contain 16800 elements is developed to confirm accuracy of finite element analysis method verification experiment procedure was carried out .the pipe was welded by single pass welding method during welding process welding pool peak temperature along the welding path were recorded at every 5 seconds at the beginning quarter of welding path and every 10 seconds at IRtec plus 2000 series infrared thermometer which was bounded with welding torch. The result shows that sharp increase in peak temperature at the beginning of welding journey after that peak temperature come to a stable stage with slight fluctuation during welding process. It is seen that the axial stresses for all four position at outer surface welding center line is tensile stresses at 0, 90, 180,270 positions. It is seen that axi symmetric stresses of axi symmetric stresses is similar to residual stresses in 3D model.

A.H Yaghi , T H Hyde , A A Becker, J A Williums ,W. Sun [3]

In this paper a brief review of weld simulation and residual stress modeling using finite element method is done. Two models which are asymmetric butt welds in p91 steel pipes having 4 or 36 pass weld in pipe with wall thickness of 7.1 and 40.00mm are considered. Fe model with inside radius to wall thickness ratio ranging from 1 to 100 have been analyzed to investigate the effect of pipe diameter on residual stresses. finite element analysis consist of thermal analysis which represents the thermal process and provides time dependant temperature distribution associated with welding followed by structural analysis which takes the temperature distribution as thermal input to calculate residual stresses. In thermal analysis the welding process is primarily simulated by Appling a distributed heat flux to weld element. The heat flux is assumed to reach its peak value from zero in a straight line followed by straight line from peak back to zero. DFLUX= $\frac{Q\gamma}{v}$ the thermal analysis processes DFLUX as the input data and delivers a set of temperature contours as output files. Structural analysis use this set of temperature contours as input and provide structural output file containing the required residual stresses strains and deformations. The results shows that the peak tensile stress occurs nearer to the inside surface of pipe in thin walls and nearer to outside surface of the pipe in thick walls. peak compressive stresses occurs nearer to the outside surface of pipe in thin walls and nearer to inside surface of the pipe in thick walls .it is also observed that the residual axial and hoop stresses are generally influenced by pipe diameter in thin walled FE model and at the inside surface in the thick walled FE model.

R D Haigh , M T Hutching , J A James , S Ganguly [4]

In this paper the residual stress distribution has been measured in two girth welded austenitic steel pipes weldments using time of flight neutron diffraction .one had weld filler metal deposited up to half the pipe wall thickness and one had weld filler metal deposited up to full of the pipe wall thickness. The aim of work is to evaluate the evolution of residual stress profile on filling the weld. The residual stress distribution measured using neutron diffraction are compared with those calculated by finite element modeling and with the results of near surface measurement using x ray diffraction. in this work two girth welded pipe weldments were fabricated using type 304 austenitic stainless steel , with dimensions of 305 mm outer diameter 25 mm wall thickness and 500 mm length each weldment were formed by TIG welding two pipe sections together multi-pass weld layers were deposited into the groove between two pipe sections .in order to define the positions at which the residual strain were measured and the residual stress calculated the coordinate axis were defined .the neutron diffraction measurements were made using the engin-x TOF instruments . the polychromatic neutron beam enters the instrument from the neutron guide through an incident split aperture which along the focusing slits apertures before the two detectors defines the volume of sample probe the beam diffracted from that part of the sample in gauge volume enters two detectors banks at 90 on either sides of incident beam. The TOF technique allows simultaneous measurement of many diffraction peaks and the diffraction pattern obtained is simultaneously analyzed from the measurement of lattice parameter a and stress free sample a0 the elastic lattice strains are measured. The principal strain and stress directions have been assumed to lie along the axial hoop and the radial directions of the weldments. using the values of a found from the Pawley fit to five diffraction peak (222,311,220,200,111) and corresponding values of the strain component at each measurement position were measured the strain component were converted to stress component using values E=209 gpa and poisons ratio= 0.30.the finite element modeling of residual stress was performed for both half filled and full filled weldments using abaqus software. The neutron diffraction measurement in half filled weldment shows that the axial stress component is compressive near the inner surface less so in mid depth but become tensile at outer surface. The stress maps obtained in full filled weldment are again generally symmetric for the axial stress component and radial component while hoop component shows tensile peak at centre.

Yasher Javadi , Hamed Salami, Pirzaman Mohammadreza , Hadizadeh Raeisi [5]

This paper investigates ultrasonic method in axial and hoop stress measurement through thickness of austenitic stainless steel pipe. Longitudinal critically refracted waves are employed to measure the welding residual stresses while outer and inner surfaces of the pipe are inspected using different frequency range of ultrasonic transducers. Welding process of the pipe is simulated by 3D FEA model. Residual stresses are measured using LCR technique the experimental setup consist of transmitter transducer and receiver transducer. Longitudinal waves are propagated at first critical angle by transmitter and then travel parallel the tested material surface before detecting by receiver. $\Delta\sigma = \frac{E}{Lt_0}(t - t_0 - \Delta t_T)$ is the relation between travel time change of LCR wave and corresponding uniaxial stress. Where Δσ - Stress change E-Elastic modulus, L-Acoustolastic constant for longitudinal wave propagating in direction of applied in direction of applied stress field ,t-Experimental travel time which is measured of welded structure t_0 -Travel time of stress free sample Δt_T -temperature difference effect between measurement temperature and room temperature on travel time. Two 500 mm length pipes of 304L are welded wit OD 320 mm and thickness of 10 mm are used to acoustoelastic constant measurement. In this paper shows that ultrasonic measurement is useful for residual stress measurement up to 2 mm from surface so both side measurements should be used for thick material.

III.RESIDUAL STRESS MEASUREMENT TECHNIQUES

During the past many years many different methods for measuring the residual stresses in different types of component have been developed .some methods are,

1) Hole-drilling technique
2) Deep hole method
3) X-ray diffraction method
4) Neutron diffraction method
5) Ultrasonic method

3.1 Hole-Drilling Technique

The hole-drilling method is relatively simple and quick; it is one of the most popularly used semi destructive methods of residual stress evaluation which can provide the measurement of residual stress distribution across the thickness in magnitude, direction and sense. It has the advantages of good accuracy and reliability, standardized test procedures, and convenient practical implementation. The damage caused to the specimen is localized to the small, drilled hole, and is often tolerable or repairable. The principle involves introduction of a small hole (of about 1.8 mm diameter and up to about 2.0 mm deep) at the location where residual stresses are to be measured. Due to drilling of the hole the locked up residual stresses are relieved and the corresponding strains on the surface are measured using suitable strain gauges bonded around the hole on the surface. From the strains measured around the hole, the residual stresses are calculated using appropriate calibration constants derived for the particular type of strain gauge rosette used as well as the most suitable analysis procedure for the type of stresses expected.

3.2 Deep Hole Method

The deep hole method is a further variant procedure that combines elements of both the hole-drilling and ring-core methods. In the deep-hole method, a hole is first drilled through the thickness of the component. The diameter of the hole is measured accurately and then a core of material around the hole is trepanned out, relaxing the residual stresses in the core. The diameter of the hole is re-measured allowing finally the residual stresses to be calculated from the change in diameter of the hole. The deep hole method is classified as a semi destructive method of residual stresses measurement since although a hole is left in the component, the diameter of the hole can be quite small and could coincide with a hole that needs to be machined subsequently. The main feature of the method is that it enables the measurement of deep interior stresses. The specimens can be quite large, for example, steel and aluminium castings weighing several tons.

3.3 X-Ray Diffraction Method

The X-ray method is a non destructive technique for the measurement of residual stresses on the surface of materials. X-ray diffraction techniques exploit the fact that when a metal is under stress, applied or residual stress, the resulting elastic strains cause the atomic planes in the metallic crystal structure to change their spacing. X-ray diffraction can directly measure this inter-planar atomic spacing; from this quantity, the total stress on the metal can then be obtained. Since metals are composed of atoms arranged in a regular three-dimensional array to form a crystal, most metal components of practical concern consist of many tiny crystallites (grains), randomly oriented with respect to their crystalline arrangement and fused together to make a bulk solid. When such a polycrystalline metal is placed under stress, elastic strains are produced in the crystal lattice of the individual crystallites. In other words, an externally applied stress or one residual within the material, when bellow the yield strength of the material, is taken up by inter-atomic strains in the crystals by knowing the elastic constants of the material and assuming that stress is proportional to strain, a reasonable assumption for most metals and alloys of practical concern . Therefore, X-ray diffraction residual stresses measurement is applicable to materials that are crystalline, relatively fine grained, and produces diffraction for any orientation of the sample surface.

3.4 Neutron Diffraction Method

Neutron diffractions method is very similar to the X-ray method as it relies on elastic deformations within a polycrystalline material that cause changes in the spacing of the lattice planes from their stress-free condition. The application of neutron diffraction in solving engineering relevant problems has become widespread over the past two decades. The advantage of the neutron diffraction methods in comparison with the X-ray technique is its lager penetration depth. In fact the X-ray diffraction technique has limits in measuring residual stresses through the thickness of a welded structure. On the other hand, a neutron is able to penetrate a few centimeters into the inside of a material, thus it can be applied widely to evaluate an internal residual stress of materials. It enables the measurement of residual stresses at near-surface depths around 0.2 mm down to bulk measurement of up to 100mm in aluminium or 25 mm in steel. This is especially useful for alloys of high average atomic number because the penetration of X-rays falls off rapidly in this regime. With high spatial resolution, the neutron diffraction method can provide complete three dimensional maps of the residual stresses.

3.5 Ultrasonic Method

One of the promising directions in the development of non destructive techniques for residual stresses measurement is the application of ultrasound. Ultrasonic method, called also refracted longitudinal (LCR) wave techniques, is not limited by the types of material understudy and can be utilized for residual stresses measurements on thick samples. Ultrasonic stress measurement techniques are based on the acoustic-elasticity effect, according to which the velocity of elastic wave propagation in solids is dependent on the mechanical stress. The most important advantages of the development technique and equipment are the possibility to determinate the residual and applied stresses in samples and real structure elements. Different configurations of ultrasonic equipment can be used for residual stresses measurements. Overall, waves are launched by a transmitting transducer, propagate through a region of the material, and are detected by a receiving transducer.

IV. THEORETICAL ASPECTS

4.1 Transient Thermal Analysis

The governing equation for transient heat transfer analysis during welding process is given by Eq.

$$\left(\frac{\partial R_x}{\partial x}+\frac{\partial R_y}{\partial y}+\frac{\partial R_z}{\partial z}\right) + Q\,(x,y,z,t) = \rho C\,\frac{\partial T(x,y,z,t)}{\partial t} \qquad (1)$$

Where R_x R_y R_z are rate of heat flow per unit area T(x,y,z) is the current temperature Q(x,y,z) is the rate of internal heat generation ρ is the density C is the specific heat t is the time. The model can then be completed by introducing the Fourier heat flow as

$$R_x = -K_x\frac{\partial T}{\partial x} \qquad (2a)$$

$$R_y = -K_y\frac{\partial T}{\partial y} \qquad (2b)$$

$$R_z = -K_z\frac{\partial T}{\partial z} \qquad (2c)$$

Where K_x K_y K_z are thermal conductivities in the x y z direction respectively generally the material parameters K_x K_y K_z ρ and C are temperature dependant. Inserting eq.2 in eq.1 yields

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z\frac{\partial T}{\partial z}\right) + Q = \rho C\,\frac{\partial T}{\partial t} \qquad (3)$$

This is the governing differential equation of the problem boundary conditions such as heat transfer by conduction, heat losses due to convection and radiation and heat input from the welding torch along with the effects of filler metal deposition, is of paramount importance for the determination of realistic temperature profiles. The general solution is obtained by applying the following initial and final boundary condition,

$$T(x,y,z,o) = T_0\,(x,y,z) \qquad .(4)$$

$$\left(K_x\frac{\partial T}{\partial x}N_x\right)+\left(K_y\frac{\partial T}{\partial y}N_y\right)+\left(K_z\frac{\partial T}{\partial z}N_z\right) + q_s + h_c(T - T_\infty) + h_r(T - T_\infty) = 0 \qquad (5)$$

Where,

$$h_r = \sigma\epsilon F\,(T^2 + T_r^2)\,(T + T_r) \qquad (6)$$

N_x , N_y , N_z are direction cosines of outward drawn normal to the boundary , h_c convection heat transfer coefficient , h_r radiation heat transfer coefficient q_s is the boundary heat flux , T_{∞} is the surrounding temperature , T_r is the temperature of the radiation heat source .

4.2 Elasto-Plastic Mechanical Analysis

The thermal elasto-plastic material model based on the von mises yield criterion and the isotropic strain hardening rule is considered stress strain relations are expressed as

$$[d\sigma] = [D^{ep}]\,[d\epsilon] - [C^{th}]\,dT \qquad (7)$$

$$[D^{ep}] = [D^{e}] + [D^{p}] \qquad (8)$$

$[D^{e}]$ - elastic stiffness matrix
$[D^{p}]$ - plastic stiffness matrix
$[C^{th}]$ - thermal stiffness matrix
$[d\sigma]$ - stress increment
$[d\epsilon]$ - strain increment
dT - temperature increment

V. MODEL PREPARATION

The pipe weldment is to be fabricated using stainless steel pipe of type 304 stainless steel with dimensions of 150 mm outer diameter 7 mm thickness and 400 mm length each weldment is formed by TIG welding two pipe sections together multi-pass weld layer is used for welding pipe sections.

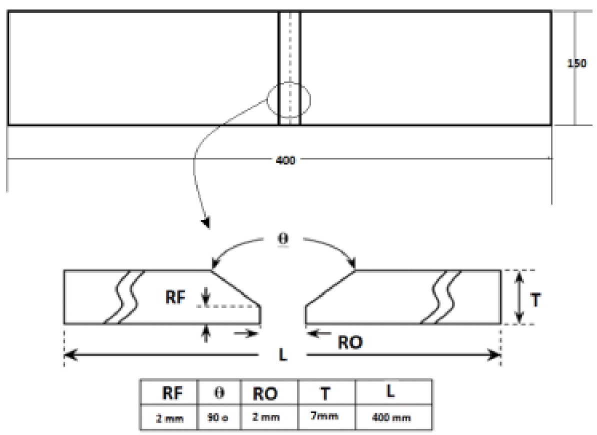

Fig 5.1 Dimensional Details Of The Pipe Specimens (Not To The Scale)

Butt weld joint geometry is shown in figure. Multi pass butt-weld geometry is used with single "V" groove having included angle of 90^{o} and 2 mm root opening as shown in Figure. The welding specimen consists of two 150 mm outer diameter and 7 mm wall thickness cylinders.

Welding will be done using robotic TIG welding system with advanced control system because use of robotic TIG welding system provides good accuracy in determining welding parameters which will be used for finite element simulation.

Grade 304 stainless steel pipes are the most versatile and the most widely used of all stainless steel pipes. Its chemical composition, mechanical properties, weldability and corrosion/oxidation resistance provide the best all-round performance stainless steel at relatively low cost.

Table 5.1 Typical Compositional Ranges for Grade 304 Stainless Steel

Grade	C	MN	SI	P	S	CR	NI	N
Min	-	-	-	-	-	18.0	8.0	-
Max	0.08	2.0	0.75	0.045	0.030	20.0	10.5	0.1

Table 5.2 Mechanical Properties of 304 Grade Stainless Steel

Grade	Tensile strength Mpa min	Yield strength 0.2% proof (Mpa) min yield	Elongation (% in 50mm) min	Hardness	
				Rockwell B (HR B) max	Brinell (HB) max
304	515	205	40	92	201

5.1 Robotic Welding Setup

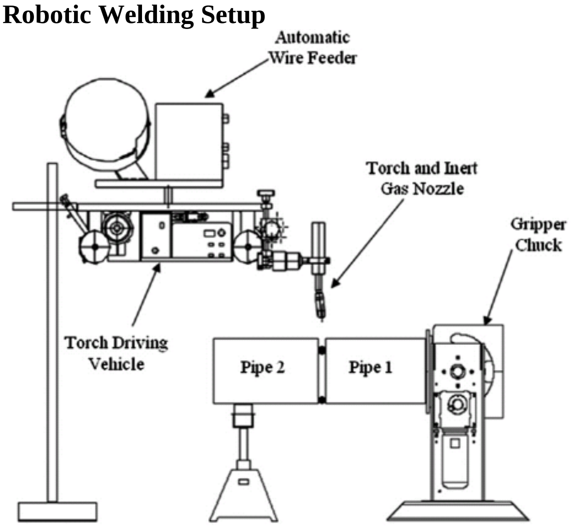

Fig 5.2 Robotic Welding System

Robotic TIG welding system has advance control system. This control system controls the power source, gripper chuck, torch driving vehicle, inert gas supplier, and automatic wire feeder. Welding by this automatic welding system provides good accuracy in determining the welding parameters which will be useful in finite element analysis.

VI. FINITE ELEMENT ANALYSIS BY ANSYS

Finite Element Approach

ANSYS is comprehensive general purpose finite element analysis software which capable of performing structural, heat transfer, fluid flow, electromagnetism and biomedical analysis and electromagnetic analyses, as well as solutions for transient impact analysis. The ANSYS version has multiple windows incorporating Graphics users interface, pull down menus, dialog box and tool bar.

6.1 Procedure In Modeling ANSYS

There are major and sub important steps in ANSYS model, pre-processing, solution stage and post-processing stage.

FE-Analysis Steps

1. Geometry Definition
2. Geometry Idealization
3. Mesh Generation
4. Analysis
5. Post Processing

6.1.1 Idealization Specification

This is sub-stepping procedure in model context represents a 3D solid definition. This model is optimized for rapid FEM analysis and is composed of 2D geometry, beam surface model. It is easy to locate and calculate the numerical position in solid geometry; beam solid model can be defined of the 3D definition. The analysis type is defined as modal.

6.1.2 Mesh Generation

The generation of a mesh on the idealized geometry is done through meshed model. The meshing depend on the configuration for the model, the general rules are carried out by setting a density for the mesh. In this application, loads and boundary conditions are added in the input file. The solver input file consists of mesh elements, nodes and load cases. The input file is generated from the application containing mesh elements, nodes and boundary conditions are added to the file.

6.1.3 Analysis

This is a stage where solution was conducted. It was the step to pre-processing and different stages of analysis took place. The load is applied to edges of beam, this was easier to implement in SOLID model. And the other entire complex algorithm in FEM solved.

6.1.4 Post-processing

At this stage the results of analysis are obtained numerically and graphically.

VII. SUMMARY

The main goal of this paper is evaluation of hoop and axial residual residual stresses in a stainless steel pipe.there are many methods available for residual stress measurement.
Hole drilling method will be used for stress measurement and results will be validated with computational results.

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