International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:14, No:6, 2020

Evaluation of Deformable Boundary Condition Using Finite Element Method and Impact Test for Steel Tubes

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***Abstract*—**Stainless steel pipelines are crucial components to transportation and storage in the oil and gas industry. However, the rise of random attacks and vandalism on these pipes for their valuable transport has led to more security and protection for incoming surface impacts. These surface impacts can lead to large global deformations of the pipe and place the pipe under strain, causing the eventual failure of the pipeline. Therefore, understanding how these surface impact loads affect the pipes is vital to improving the pipes' security and protection. In this study, experimental test and finite element analysis (FEA) have been carried out on EN3B stainless steel specimens to study the impact behaviour. Low velocity impact tests at 9 m/s with 16 kg dome impactor was used to simulate for high momentum impact for localised failure. FEA models of clamped and deformable boundaries were modelled to study the effect of the boundaries on the pipes impact behaviour on its impact resistance, using experimental and FEA approach. Comparison of experimental and FE simulation shows good correlation to the deformable boundaries in order to validate the robustness of the FE model to be implemented in pipe models with complex anisotropic structure.

***Keywords*—**Dynamic impact, deformable boundary conditions, finite element modeling, FEM, finite element, FE, LS-DYNA, Stainless steel pipe.

I. Introduction

STEEL pipes have been traditionally used and still implemented in vast segments of oil and gas industry in onshore and offshore oil transport and refineries, for transporting oil and gases at various pressure conditions. Due to their volatile operating conditions, they are susceptible to damages, leaking or explosion. If a pipe is impacted from an object at high velocity, it can lead to cracking of the pipe, which can lead to rapid subsequent failure or fire or explosion leading to severe environmental damages. Therefore, it becomes inevitable to study the dynamic behavior of these pipes under impact loadings to evaluate their resilience under localised high-speed impactor.

Impact loading cases on steel pipes have been studied in the past [1]-[5]. Most of the previous impact studies were carried out on empty pipes focusing on the radial impact penetration. A study was done on fully clamped empty mild steel pipes subjected to lateral loading [4]. Another study carried out on dynamic penetration test on steel tubes by hemispherical-shaped projectiles to study the effect on failure mode, projectile mass and its nose radius were studied [1].

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Experimental analysis is the most sought-after method of investigating the dynamic behaviour of pipes. A series of low-velocity impact tests were carried out on pressurised pipes to study its effect on the internal pressure, which were fully clamped and impacted laterally by a wedged indenter [3]. The results showed that impacts of lower velocity caused permanent plastic deformation on the pipes but impacts of larger velocity ruptured the pipe integrity completely at the point of contact or at the supports.

Low velocity impact on the pipe on the radial direction can initiate significant damage in the form of dents and material fracture and is a cause for rapid material failure. Steel pipes are assembled in line using variety of supporting methods. Clamping, however, is a common way to create a localised hold where surface unevenness cannot be avoided. There is yet a very limited research data to suggest the effect of boundary conditions on impact behaviour, energy absorption capacity and resilience of pipes.

In this work, a numerical model considering deformation and contact force is presented to study the effect of a deformable boundary condition on the impact absorption capabilities on steel pipes. This study investigates the impact behaviour of a steel pipe in transverse loading condition with deformable boundary condition. Based on the results, the study proposes to construct a numerical model to predict the impact behaviour for deformable boundary condition. The model can be further used as a design tool to select the best parameters for optimum impact resilience. Experimental parameters for the conditions are specified such as impact velocity, impactor weight, geometry, whereas the deformable boundary condition is studied for this study. Deformation and contact force are primary focus in the impact response. The behaviour is presented in contact force-time, deformation-time and impact energy-time.

II. Test Method

The sample used for testing was 1 m long pipe section cut from commercially available stainless steel EN3B. The pipes had internal diameter of 4 in (101.6 mm) and wall thickness 2 mm. Single impact low velocity impact tests were performed on the pipes using a free fall drop weight impact system (modified D2444) that was modified for a dynamic testing mechanism [6]. A 10 cm diameter dome impactor was used as the impactor.

The contact force was measured with a load transducer located on the impactor neck. Impact tests were done to replicate a dynamic impact scenario in real life in low velocity with speeds up to 10 m/s but with a short impact time to achieve high impact energy. Impactor mass of 16 kg was used for impact tests. The tests were then carried out to examine the impact behaviour of the pipe.

Fig. 1 Impact Test Setup

The mechanical properties of the EN3B steel are shown in Table I.

TABLE I
PIPE MECHANICAL PROPERTIES

Quantity	Symbol	Stainless Steel (EN3B)
Density	r	7076.01kg/m^3
Young's modulus	E	210 GPa
Poisson's Ratio	nu	0.303
Yield Stress	E	440 MPa

Using a mechanical 3D scanner, a coordinate acquisition process was performed after each to render a wireframe model of the post-impact sample and compare the damaged zone with numerical model. The experiment helped acquiring the impact velocity, impact energy and deflection on the maximum level.

III. Finite Element Modelling Simulation

As the experiment occurs at a high speed and the cost of performing the experiment is high, the numerical model can offer more economic approach to the design with additional information about the behaviour of the pipe subjected to lateral loading. Base model on similar experiments was modified from previous literature [1], [6]. The numerical model helped predict the failure stresses and forces induced by the pipe and the boundary straps, which was one of the primary focuses of the study as a result of the impact projectile. LS-Primer finite element was used to design and process the simulation.

Mat_024(Piecewise Linear Plasticity) was used to model the steel pipe in the contraption modelling due to its isotropic nature and simple nature of design model. Maximum stress criterion is used to determine when the pipe fails, once the yield stress is achieved after impact. For this simulation condition, SURFACE_TO_SURFACE(STS) and SINGLE_ SURFACE were implemented, with coefficient of friction specified for the type of contact [7].

A. Boundary Conditions and Loading

The study examines the effect of deformable boundary on the difference in behaviour of the impact on the transverse plane recoding stress on boundary region and overall global deformation. For the Finite Element Model, the base of the support was constrained in the translational direction to prevent body motion and remainder nodes could move at both ends.

B. Tensile Testing

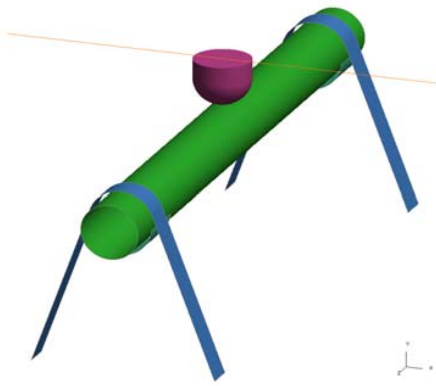

Fig. 2 Finite Element Model Setup

Fig. 3 Post Impact Sample

IV. Results

A. Dynamic Test Response of the Pipes

The Load-Time and Displacement-Time graphs have been shown in Figs. 4 and 5 which show the impact load rises sharply at the beginning of the impact and then increases steadily till it reaches maximum impact load. The impactor load decreases to zero when the impactor hits the surface of the pipe. Based on close observations of the test specimens, the pipe showed ductile failure at the impact point. The samples were analysed post testing for global deformation for comparison with FE modelling showing good correlation between numerical and experimental test.

The FE Models correlation with the physical test showed good correlation with the load-time graphs.

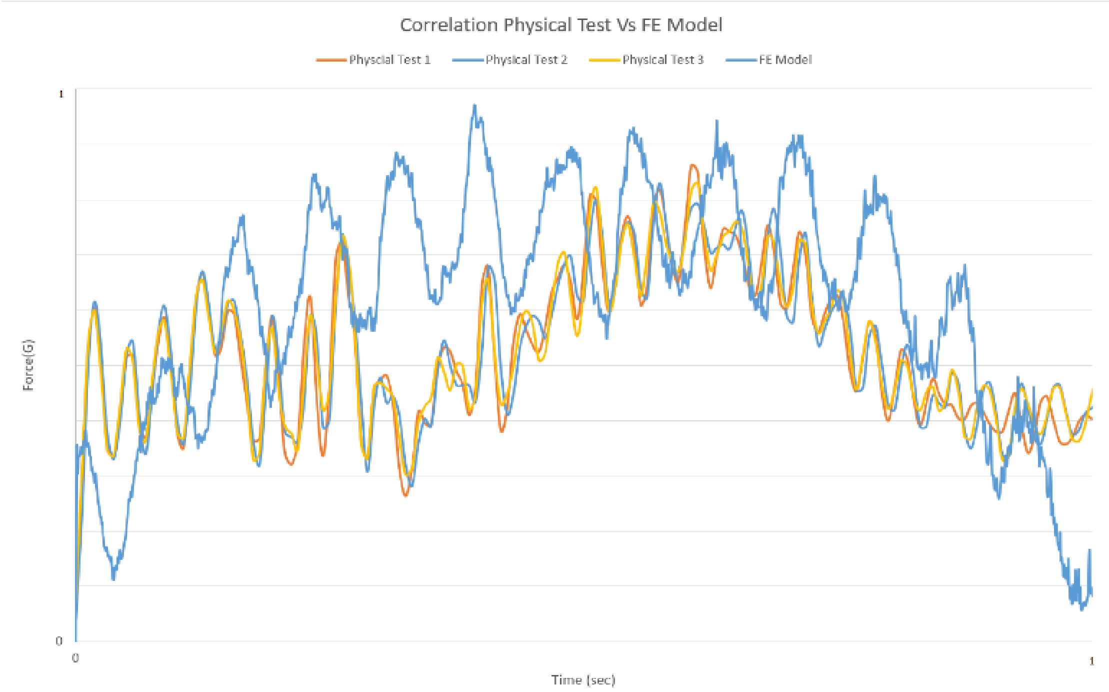

Fig. 4 Force vs. Time response to impact experimental and numerical correlation

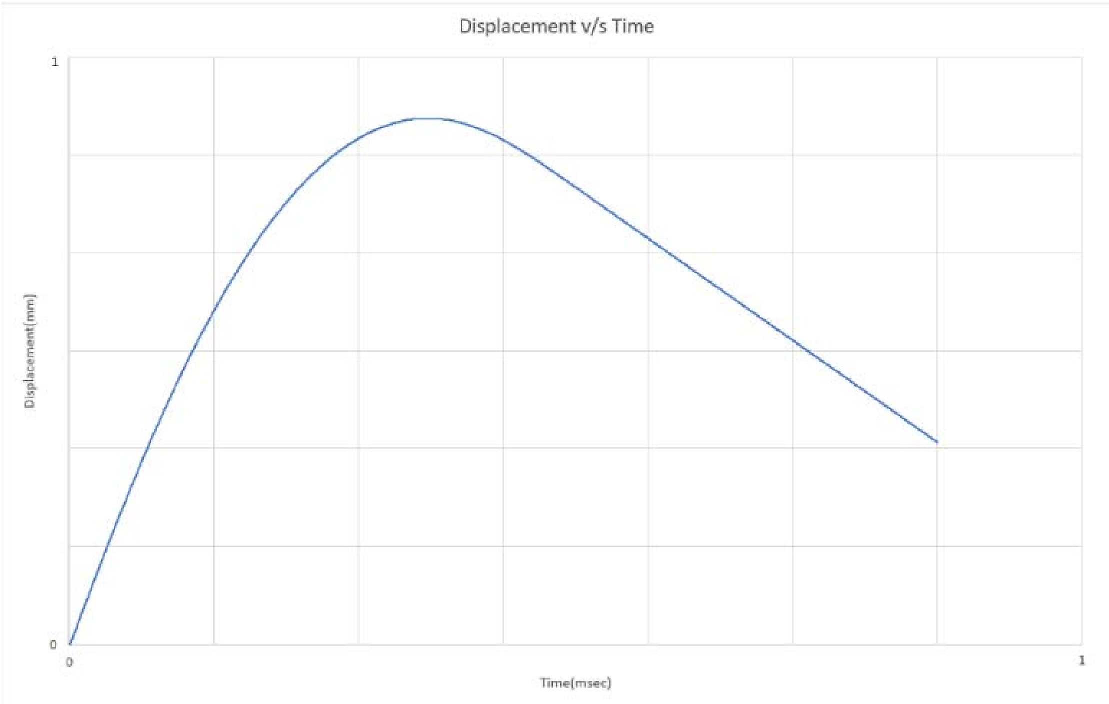

Fig. 5 Displacement-Time Graph

V. Discussion

From the impact testing with deformable boundary condition, the sample was loaded on a coordinate mapping machine to make a wireframe of the impacted zone to analyse the damaged structure, The wireframe, Fig. 7, shows the local deformation of the damaged section of the pipe which was then compared with the FE model.

From Fig. 5, the pipe showed to absorb more of the impact energy and minimise the risk of failure by distributing the impact load around the edges and cradled points around the cradle points and retaining much of its structural integrity.

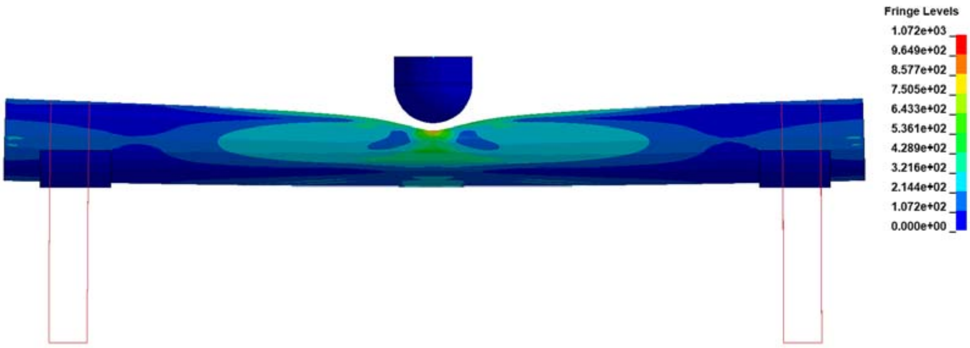

Fig. 6 Stress Distribution on FE model of the impacted area

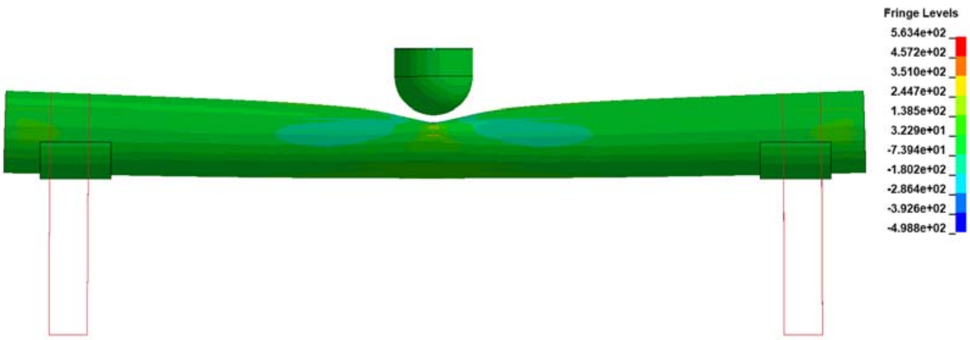

Fig. 7 FE model of the Sample's Impacted zone post test

Fig. 8 Physical sample post test

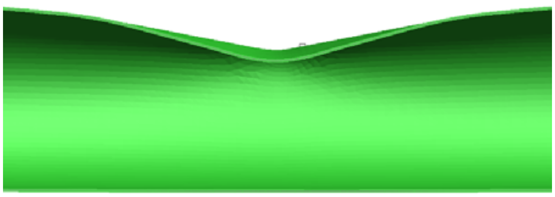

Fig. 9 FE model of the Sample's Impacted zone post test

VI. Conclusion

Most FE models in similar studies use fixed boundary conditions. This study has two aims:

1. The first aim is to investigate the possibility of instead implementing elastic deformable, rather than fixed, boundary conditions in a pipe impact test.
2. The second aim is to validate these elastic deformable boundary condition models against experimental data.

The results presented in this study show that it is possible to instead use deformable boundary conditions, and that there is a good correlation between the FE model results and experimental data numerically and geometrically.

In future studies, researchers can create FE models of pipe impact tests which implement these new elastic deformable boundary conditions, and which also represent complex pipe structures (i.e. including composite layers within the pipe).

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