Numerical Simulation of Functionally-Graded-Material Pipes Under Blast Loading

Elias Ali[1(✉)] and Girum Urgessa[2]

[1] Department of Civil and Environmental Engineering, The University of Alabama in Huntsville, Huntsville, AL, USA
elias.ali@uah.edu
[2] Department of Civil, Environmental and Infrastructural Engineering, George Mason University, Fairfax, VA, USA
gurgessa@gmu.edu

Abstract. The behavior of thin-walled pipes made from Functionally Graded Materials (FGMs) under localized blast loading was examined through numerical simulation. FGMs are advanced composite materials, which possess continuous variation of material properties in the thickness direction. FGM pipes with varying thicknesses and diameters subjected to blast loads from a 0.1 kg TNT charge at varying stand-off distances of detonations were considered. The composition of the FGM pipes was defined by using the volume fractions of the constituent materials distributed across the thickness. The general rule of mixtures was used to predict the material property of the FGM pipes. The pipes were assumed to be restrained for both translation and rotation at their ends. Finite element modeling was conducted using the coupled Eulerian-Lagrangian (CEL) approach. The influence of constituent material gradation on blast response was also examined. The results of this investigation demonstrate a potential application of FGMs as thin-walled structural elements in the future development of a resilient pipeline infrastructure under extreme loadings.

Keywords: Functionally graded materials (FGMs) · Composites · Pipeline · Blast · Coupled Eulerian-Lagrangian (CEL)

1 Introduction

In the past two decades, according to the report from the U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration, PHMSA (2021), more than 12,507 significant pipeline incidents and explosions have killed at least 283 people, injured 1180, and caused approximately ten billion dollars in damages in the USA alone in the last two decades. The integrity and stability of key infrastructures such as gas pipelines can be compromised by defects arising mainly from corrosion (external, e.g. old pipes), (internal, e.g. type of fluid), maximum operating pressure, defects (manufacturing, and construction-welding/fabrication defects), third-party mechanical damage,

weather and outside forces. With growing pressure on the industry, there is a huge interest among researchers in developing a new composite material to keep infrastructures more resilient for unplanned accidents such as an explosion.

Functionally graded materials (FGMs) are advanced materials characterized by the non-homogenous material system with a gradual gradation of material property within a given dimension. Considered the "holy grail" of composite materials, FGMs can be continually produced by varying the constituent multi-phase materials in a predetermined profile. This gradation is achieved by either combining two or more materials using volume-fraction or by treating a single material chemically to change its initial properties. The functionally graded composite material will then have a unique and different material property from the individual constituent materials while preserving their benefits. The concept of FGM first originated in Japan in 1984 where it was used in hypersonic spaceplane projects as a thermal barrier to resist high-temperature gradient (with an outside temperature of 2000 °K and inside temperature of 1000 °K across less than 10 mm thickness) for space shuttles (Maalawi and Sayed 2011; Mahamood and Akinlabi 2012). Applications of FGM have been common in the last decade in the areas of aerospace, medicine, defense, energy, and optoelectronics (Mahamood and Akinlabi 2012). Even though, FGMs are considered ideal for applications involving high strain rate and thermal shock loading (Rousseau and Tippur 2001), their application on structural components and infrastructures, like gas pipes, is still in its research stage and there are only limited researches on blast loading response of FGM thin-walled structure.

Larson (2008) studied both numerically and experimentally, the impact response of functionally graded Titanium-Titanium Boride plates with seven layers of each 0.18 in.. Lee (2004) studied the stress and displacement fields for a propagating crack at constant speed along the gradient in FGMs and discussed the effects of non-homogeneity on isochromatic fringes around the crack for different propagation speeds and non-homogeneity. Zhang and Paulino (2005) investigated dynamic failure processes of three-point bending beams under impact loading and analyzed the influence of material gradation on crack initiation and propagation. Giannaros et al. (2015) studied the blast response of a glass fiber reinforced polymer pipeline and examined the deformation and damage of the pipeline under explosive impact. Chen et al. (2015) performed full-scale validation tests and numerical simulations of far-field air blast loading acting on deformable steel boxes which would help forensic methods to aid blast incident investigations. The application of FGM sheathing in thin-walled structures was investigated by (Ali and Bayleyegn 2018). Analytical and numerical buckling analysis of FGM plates made of metal and ceramic were also studied by (Ali and Bayleyegn 2019). Song et al. (2016) studied both experimentally and numerically the dynamic response of the X70 grade pipeline under localized blast loading. In their work, the influence of explosive mass, blast over-pressure contact area and pipe thickness on the deformation of the pipe were investigated.

Thus, this research work aims at providing insight and an alternative material solution in pipeline infrastructures on a localized blast loading through a numerical approach and exploring the development of a resilient civil infrastructure application of FGMs.

2 Functionally Graded Material Pipeline

The pipeline infrastructure considered in this study is composed of functionally graded materials. The pipe geometry, FGM mechanical properties, and material models assumed in the research are discussed in this section.

2.1 Mechanical Properties

In functionally graded materials the constitutive material properties are represented as a function of the variation of the volume of fractions. A typical FGM pipe can be described by the variations in volume fractions, in which the constitutive material property varying through the thickness of the pipe is expressed using volume fraction. Depending on the assumed form of expression involved in relating the volume of fractions to the material property sought after, three material models that establish mechanical properties typically adopted in FGM applications are examined.

2.1.1 FGM Material Models

2.1.1.1 Power-Law Model

The volume fraction variation of FGM pipe within a given direction in the power-law function can be described using the form of expression given in Eq. (1) where z is any point within a given direction, h is the total thickness of the FGM pipe, and n is a power-law index parameter.

$$f(z) = \left(\frac{z + h/2}{h} \right)^n \tag{1}$$

Once the local volume fraction is defined, the functional relation of material properties such as modulus of elasticity E, Poisson's ratio υ, and density ρ, at any point across the pipe thickness can be expressed according to the general rule of mixtures. The Young's modulus variation for P-FGM, $E(z)$, can be calculated by using Eq. (2).

$$E(z) = E_1 f(z) + (1 - f(z))E_2 \tag{2}$$

where E_1 and E_2 are Young's moduli of the FGM at the bottom ($h/2$) and top ($-h/2$) surfaces.

The variation of volume fraction $f(z)$ for one of the two constituent materials (metal) making up the FGM matrix and variation in the Youngs modulus in the P-FGM model are shown in Fig. 1. This implies the second material will have a volume fraction of $1-f(z)$ at a given location across a thickness (if the desired graduation is within a thickness direction). It can also be noticed that for every power-index value (n) considered, the FGM matrix will have 100% of one material at the top and 100% of the second material at the bottom.

2.1.1.2 Sigmoid Model

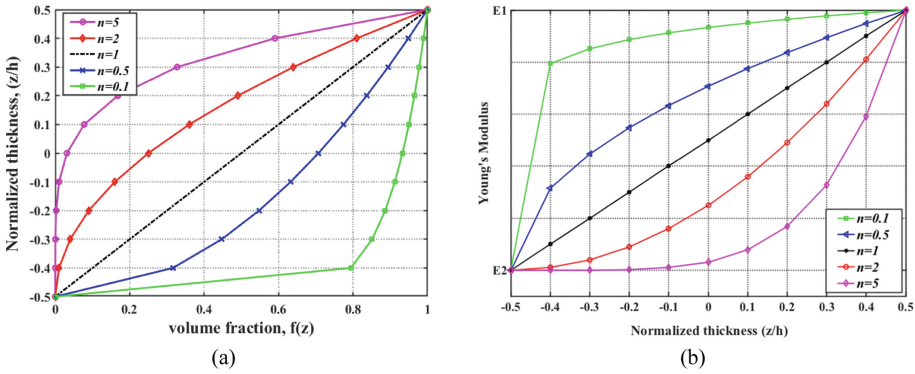In the case of adding an FGM of a single power-law function to the multi-layered

Fig. 1. Material properties variation in P-FGM: (a) P-FGM volume fractions and (b) Young's modulus**.**

composite, stress concentrations appear on one of the interfaces where the material is continuous but changes rapidly. Chi and Chung (2006) defined the volume fraction using two power-law functions to ensure the smooth distribution of stresses among all the interfaces. The two power-law functions are defined by (Fig. 2):

$$f_1(z) = 1 - \frac{1}{2}\left(\frac{\frac{h}{2} - z}{\frac{h}{2}}\right)^P \quad for\ 0 \le z \le \frac{h}{2} \tag{3}$$

$$f_2(z) = \frac{1}{2}\left(\frac{\frac{h}{2} + z}{\frac{h}{2}}\right)^P \quad for\ -\frac{h}{2} \le z \le 0 \tag{4}$$
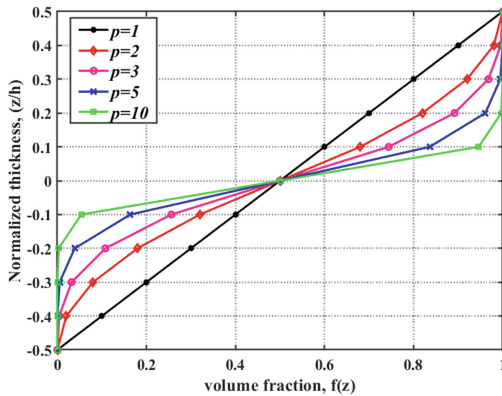

Fig. 2. Variation of Young's modulus in S-FGM.

The Young's modulus variation in the S-FGM can be calculated using a similar expression as P-FGM but uses two-volume fraction expressions for each part separately

as shown in Eq. (5 and 6).

$$E(z) = f_1(z)E_1 + \left[1 - f_1(z)\right]E_2 \quad for \ 0 \leq z \leq \frac{h}{2} \tag{5}$$

$$E(z) = f_2(z)E_1 + \left[1 - f_2(z)\right]E_2 \quad for \ -\frac{h}{2} \leq z \leq 0 \tag{6}$$

2.1.1.3 Exponential Model

The exponential function is the most used FGM material function among many researchers due to its simplicity in obtaining analytical solutions and the only parameter is the natural logarithm of the ratio of elastic modulus of the two materials considered. Equation (7) is used to describe the variation of elastic modulus in E-FGM (Fig. 3).

$$E(z) = E_2 e^{\beta z} \quad where \quad \beta = \frac{1}{h} \ln\left(\frac{E_1}{E_2}\right) \tag{7}$$
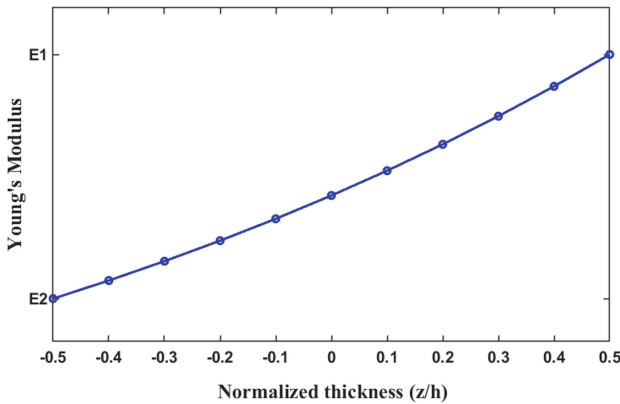

Fig. 3. Variation of Young's modulus in E-FGM.

2.1.2 Parent Materials

The FGM pipe thickness was modeled with a step-wise (eight layers) material variation and each layer across the thickness of the pipe was assumed to be composed of an isotropic and homogenous material based on the volume fraction defined. The outer pipe face material was 100% steel with Young's modulus of 203 GPa (29500 ksi) and gradually changed to 100% ceramic with Young's modulus of 380 GPa (55114 ksi). Even though the Poisson ratio is expressed using power law, its effect on the deformation across the small thickness of the pipe is insignificant compared to the effect of elastic modulus (Chi and Chung 2006) and in this paper, it was assumed to be constant ($\upsilon = 0.3$). The choice of these two materials was based on the effect of blast loading which

results in both high stress and temperature on the pipe. Steel has higher tensile stress but lowers thermal resistivity, while ceramic has higher thermal resistivity with lower stress resistance. Thus, the FGM pipe would be composed of a material property combining the benefits from the two-parent materials, in this case, metal and ceramic.

2.2 Geometry

The pipe geometry is shown in Fig. 4, with the corresponding cylindrical coordinate system. The middle pipe diameters chosen for the analysis were 101.6 mm (4 in.), 203.2 mm (8 in.), and 304.8 mm (12 in.). The pipe wall thicknesses considered were 6 mm (0.236 in.) and 8 mm (0.315 in.) for each pipe diameter. Length of pipe (L) considered equals 1016 mm (40 in.).
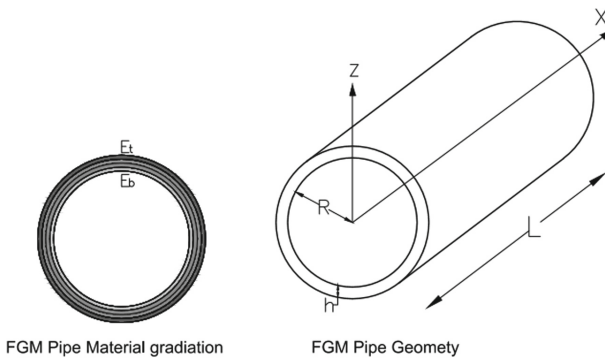

Fig. 4. FGM pipe material gradation and geometry.

3   Blast Loading Modeling

3.1 Blast FE Modeling Approach

Numerical simulation of the blast loading on the FGM pipes was performed using the recently developed Coupled Eulerian-Langrangian (CEL) modeling using ABAQUS. In the CEL modeling approach, the Lagrangian structure of interest (pipe) would be surrounded by a volume of air modeled using Eulerian elements as shown in Fig. 5. The explosive (TNT charge) creates peak overpressure on the Lagrangian material located at a distance (stand-off distance, R). In this approach shock wave (blast wave propagation) in the air domain which is equivalent to the incident blast wave that would exist at that distance away from the explosive once detonated could be fully explored and the associated structural response due to the blast waves would simultaneously be analyzed.

For the Eulerian element and 8-node linear Eulerian brick with reduced integration (EC3D8R), while for Lagrangian pipe an 8-node linear brick element (C3D8R) were used. Air and TNT materials, and in general all liquids and gases, were modeled with the use of equations of state (EOS). An equation of state is a constitutive equation that

defines the pressure as a function of the density and the internal energy. Air was modeled with, an ideal gas equation, and the TNT charge was defined by the use of the Jones-Wilkins-Lee (JWL) equation of state, which models the pressure generated by the release of chemical energy in an explosive.

$$P = A\left(1 - \frac{\omega\rho}{R_1\rho_o}\right)\exp\left(-R_1\frac{\rho_o}{\rho}\right) + B\left(1 - \frac{\omega\rho}{R_1\rho_o}\right)\exp\left(-R_2\frac{\rho_o}{\rho}\right) + \omega\frac{\rho^2}{\rho_o}E_m \quad (8)$$

where: A, B, R_1, R_2, ω (adiabatic constant) are material constants, ρ_o is the density of the explosive, ρ is the density of the detonation products, and E_m internal energy per unit mass of explosive.
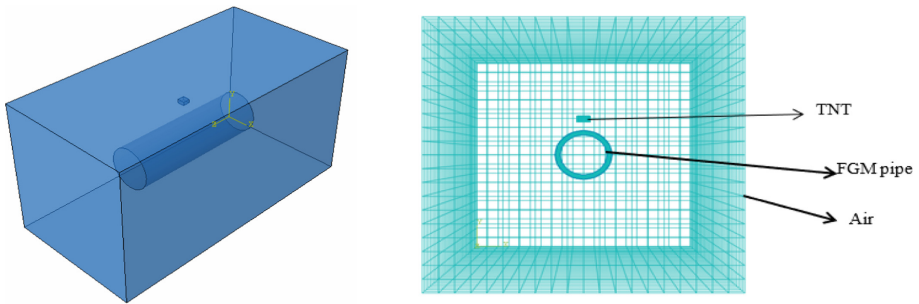

Fig. 5. CEL model representation of FGM pipe.

The proper identification of the TNT-specific energy is crucial for the reliability of analyses. The material properties (e.g. Young modulus, yield stress) which are spatially varying along the thickness of the pipe were carefully modeled in the FE simulation. The material properties for air and TNT used in the CEL modeling were taken from (Giannaros et al. 2015). The TNT charge was assumed to have a 0.0 s of delay in detonation which accounts for the time delay from the ignition of the explosive to fully explode and wave propagates to the Lagrangian parts (FGM pipe). The blast load was applied at the mid-length of the FGM pipes. The metal-rich side was modeled to be the outer pipe and gradually to the ceramic side to the inner face of the pipe. The FGM pipe was modeled as a shell element with the specific dimensions, where the boundary condition at the ends considered to be fixed-fixed, with translation and rotations constrained at the two ends of the pipe during the analysis (Fig. 6a). Each pipe thickness in the parameter study was divided into 8 layers (Fig. 6b) with each layer modeled as an isotropic and homogenous material as defined by the corresponding volume fraction.
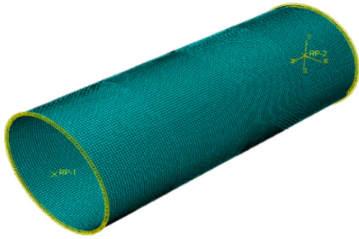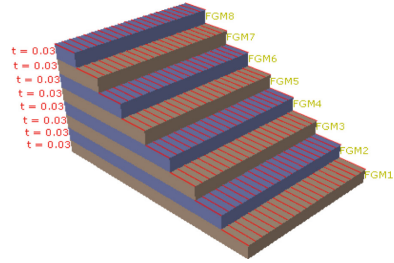
(a) ABAQUS model   (b) Ply stock plots of the FGM pipe

Fig. 6. FGM pipe finite element model details.

4 Results and Discussions

Material gradation, pipe diameter, volume fraction, material model, and pipe thickness sensitivity studies were performed and the corresponding results are discussed below.

4.1 Gradation Sensitivity

Gradation sensitivity study using the CEL approach was first investigated to examine the blast resistance of FGM in comparison with 2-layered composite pipe and uniformly graded steel pipe, as shown in Fig. 7. It was observed that the FGM pipe showed the least dynamic load-deformation at pipe mid-length followed by the two-layered composite pipe while the uniformly graded (pure steel) exhibits the largest deformation for the same blast TNT load (W = 0.1 kg), a stand-off distance of 0.5 m and pipe thickness (8 in.).
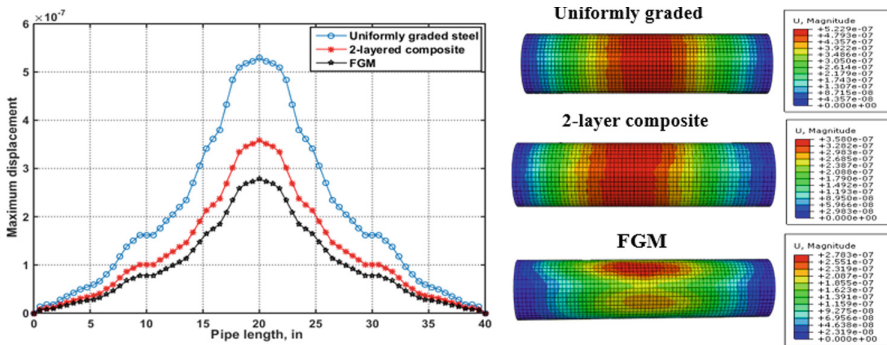

Fig. 7. Maximum displacements in *mm* and von-misses at the center of the 8 in. diameter pipe.

4.2 Pipe Diameter Sensitivity

The influence of pipe diameter on the dynamic response of FGM pipes was also examined and the simulation results are shown in Fig. 8 where the von-Mises stress (and

deformation) of the three pipes (4 in., 8 in., and 12 in.) under localized blast loading was observed to decrease with an increase in FGM pipe diameter for a given standoff distance (R), the mass of explosion (W) and volume fraction index (n). This response can be attributed to the higher bending stiffness due to the increase in the pipe diameter.
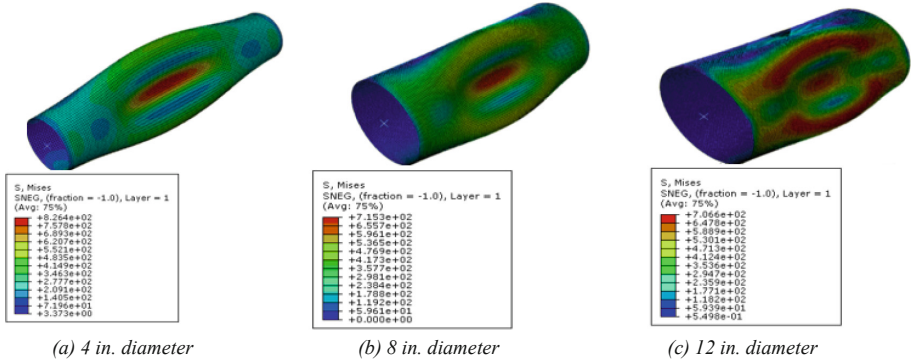

| (a) 4 in. diameter | (b) 8 in. diameter | (c) 12 in. diameter |

Fig. 8. Pipe diameter sensitivity: max deformation/Von-Mises stress in the FGM pipe.

4.3 Volume Fraction and Material Model Sensitivity

Volume fraction sensitivity of the FGM pipe composition was undertaken for comparison on the blast response of the FGM pipe as a function of the volume fraction index (n) for P-FGM pipe and volume fraction index (p) for the S-FGM pipe as shown in Fig. 9. It was observed that the dynamic response for the set of parameters (pipe diameter (d = 12 in.), standoff distance (R = 0.5 m), and TNT load (W = 0.1 kg), pipe modeled with index (n = 0.1), and (p = 2) showed the least deformations followed by n = 1.0 and p = 5.0. This means there is no direct relation between the optimum gradient of materials and accompanied deformation at the center of the pipe.
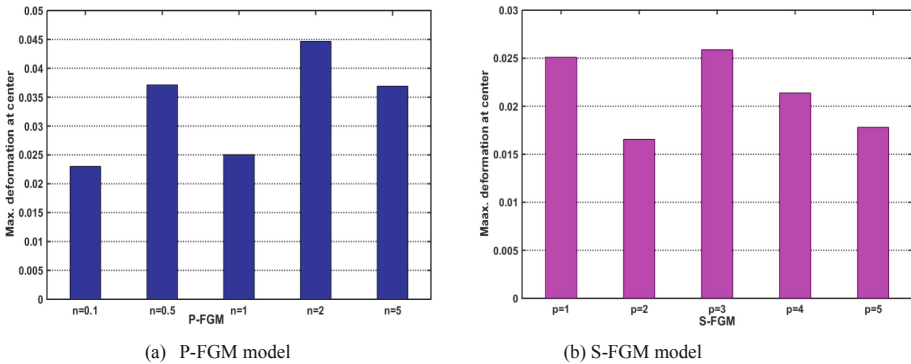

| (a) P-FGM model | (b) S-FGM model |

Fig. 9. Maximum deformation at pipe center (mm) (a) P-FGM model and (b) S-FGM model.

The dynamic responses of all three models are presented in Fig. 10 for the material variation functions of the power-law index (P-FGM), sigmoid function (S-FGM), and exponential function (E-FGM). The maximum deformation comparison was evaluated among the three models for 12-in. diameter pipe, TNT charge (W = 0.1 kg) and stand-off distance R = 0.5 m and pipe thickness = 0.236 in. (6 mm). The overall comparison between the three models shows that the S-FGM model resulted in the smallest deformation in FGM pipes. The optimum material gradation as shown in Fig. 10(a) among the selected model function was identified. It can be observed that the FGM pipe modeled with S-FGM (p = 2) resulted in the smallest deformation followed by the P-FGM pipe with (n = 0.1) and exponential function resulted in the largest deformation.
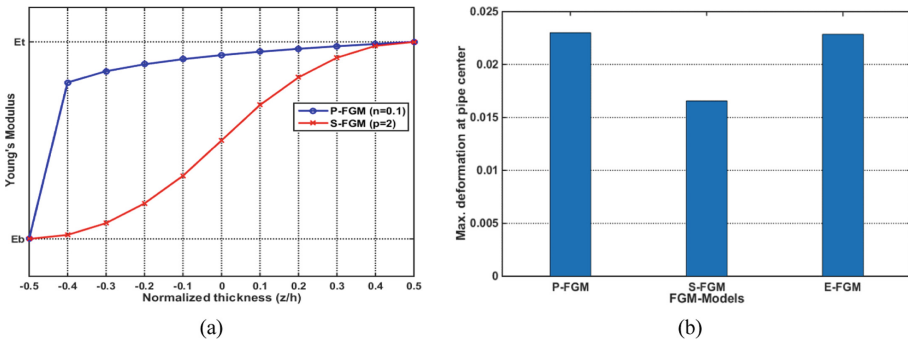

Fig. 10. (a) Optimum material gradient of FGM pipe and (b) Pipe blast response model comparison.

4.4 Pipe Thickness Sensitivity

The dynamic blast response of the FGM pipes with two different thicknesses ($t_1 = 0.236$ in. and $t_2 = 0.315$ in.) was also investigated for the FGM pipe with a diameter of 12 in., stand-off distance R = 0.5 m, and blast weight W = 0.1 kg. The maximum deformation magnitude for FGM pipe with thickness t = 0.315 in. was about 1.227 mm while for the same pipe with t = 0.236 in. the deformation is higher by 6.8% with a maximum deformation of 1.365 mm at the end of the analysis as shown in Fig. 11.

From this analysis, it can be concluded that, the thicker the pipe thickness, the smaller the expected dynamic deformation. It was also observed that the maximum deformation occurred close to mid-pipe length for both pipe thickness cases when the blast explosion is at 85 μs.
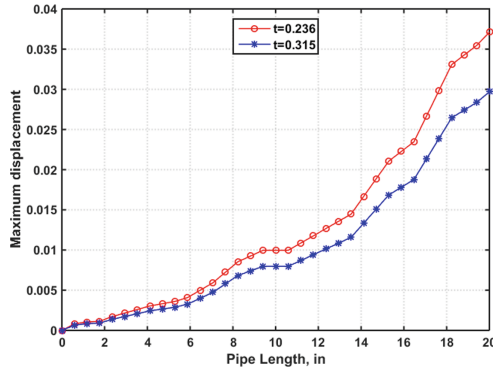
Fig. 11. Maximum displacement comparisons along pipe length for different pipe thicknesses.

5 Conclusions

The behavior of thin-walled pipes made from Functionally Graded Materials (FGMs) under localized blast loading was examined through numerical simulation. FGM pipes with varying thicknesses and diameters subjected to blast loads from a TNT charge at varying stand-off distances of detonations were considered. The general rule of mixtures was used to predict the material property of the FGM pipes using the volume fraction of parent materials from power-law, sigmoid, and exponential material functions. Finite element modeling was conducted using the coupled Eulerian-Lagrangian (CEL) approach. The influence of constituent material gradation on blast response was also examined. The results of this investigation showed that:

- FGM pipe exhibits the smallest blast load-deformation compared with uniformly graded pipe and 2-layered composite pipe.
- Sigmoid material function resulted in the smallest deformation compared with pipe modeled with P-FGM and E-FGM.
- Exponential material function resulted in the largest deformation
- For P-FGM pipe modeled with index (n = 0.1) showed the least deformation while the largest deformation has occurred with n = 2.0. This indicates that there is no direct relationship between the index value with the accompanied deformation. Thus, there needs to be an experimental investigation to validate the results presented herein.

Overall, the results from this study demonstrated a potential application of FGMs as thin-walled structural elements in the future development of a resilient pipeline infrastructure under extreme loadings.

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