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Response surface modeling to facilitate the parametric study of transversely impacted pressurized pipelines

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ABSTRACT

Finite element analyses of the transverse impact behavior of pressurized pipelines were previously performed for a variety of outside pipeline diameters and internal pressures at two spanwise locations. In this study, quadratic response surface models (RSMs) based on a full factorial statistical design were developed to predict the maximum permanent deflection, absorbed energy, and maximum force calculated for a given impact event. The RSMs were characterized in terms of two independent variables: outside diameter and internal pressure. An analysis of variance was then conducted for each response and used to determine an appropriate statistical model. The parametric study results showed that RSMs can efficiently and accurately reveal the influences of the design variables on the lateral impact response of the pressurized pipelines.

1. Introduction

In a previous preliminary study, the transverse impact behavior of mild steel pressurized pipelines was investigated using the dynamic, nonlinear finite element (FE) analysis software, LS-DYNA, for multiple outer pipeline diameters and internal pressures [1]. Seventy-two simulations were used to predict the maximum permanent deflection, absorbed energy, and maximum force throughout the impact event. Transverse impacts were simulated at two span-wise locations: the midspan and one-quarter span. The obtained computational results were verified by comparing with published experimental data [2,3]. In order to better understand how the pipeline diameter and internal pressure affect the impact response and facilitate future pipeline design optimization, polynomial response surface models (RSMs) were developed based on a full factorial statistical design [4]. During a design process, RSMs can be used to optimally determine the potential influences of key design variables on the performance or quality of an entire system. For example, Torres et al. [5] developed RSMs to optimize the fabrication procedure for vapor grown carbon nanofiber/vinyl ester nanocomposites that led to maximum impact strength. Similar studies were conducted by Lee et al. [6] and Nouranian et al. [7,8] to determine the optimal mechanical performance of the same nanocomposite system. Samarah et al. [9] developed RSMs to determine the influence of sandwich composite material and geometric parameters on the impact damage tolerance characteristics. RSMs have also been extensively applied in developing, improving, formulating, and optimizing industrial processes [10], including optimization of the energy absorption capacity of thin-walled columns during crash analyses [11–16]. In this study, RSMs were employed to determine how the outer diameter and internal pressure of mild steel pipelines affect their impact response. The approach developed in this study can be used to efficiently and accurately design pressurized pipelines.

2. Problem description

In previous FE analyses [1], a 1.5 mm rigid plate impacted a number of simulated pressurized pipelines at the midspan and one-quarter span positions. The simulated pipes were made from 2 mm thick seamless cold drawn mild steel with outer diameters (D) of 22, 42, 60, 80, 100, and 120 mm and a fixed ratio of $2L/D = 10$, where $2L$ is the distance between the two fixed supports. This ratio is considered to be the largest unsupported pipeline length ratio considered by most research laboratories and industrial plants [17]. The mechanical properties in the axial direction of the pipeline were given by the static uniaxial yield stress $\sigma_y = 663$ MPa, static ultimate tensile stress $\sigma_u = 823$ MPa, and static uniaxial rupture strain $\varepsilon_r = 6\%$. Those properties were implemented into the FEA models through the card *MAT_PLASTIC_KINEMATIC. Six different internal pressures, 0, 30, 60, 90, 120, 150 bar, were separately applied to the inner surface of the pipelines. Seventy-two FE models were then created along with appropriate boundary and initial conditions. Both ends of the pipeline FE models were fully constrained at the supports, and a 17.48 kg rigid

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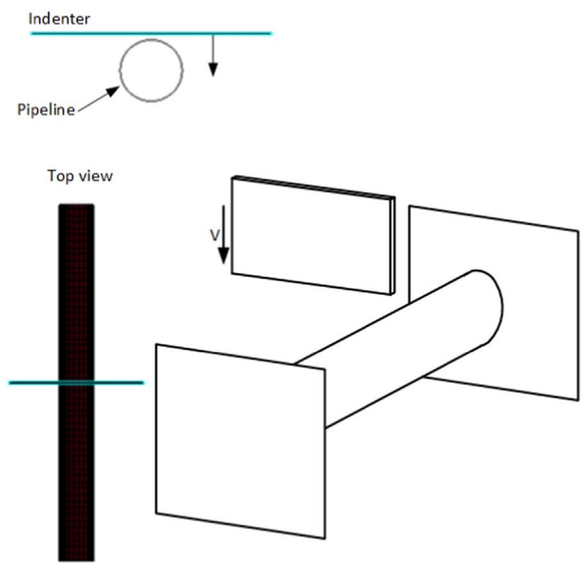

Fig. 1. FE model showing an indenter impact at the midspan of a pressurized pipeline.

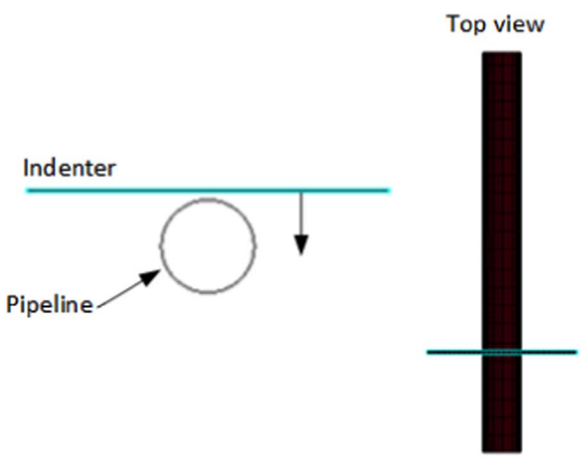

Fig. 2. FE model showing an indenter impact at the one-quarter span of a pressurized pipeline.

indenter impacted those models with an initial velocity of 10 m/s. Figs. 1 and 2 illustrate two simulated impact scenarios in which the indenter impacted a pipeline at the midspan and one-quarter span, respectively. The calculated maximum permanent deflection in the loading direction, absorbed energy, and maximum impact force are shown in Table 1 for each pipeline model. Note that for midspan impacts, negative deflections (*i.e.*, opposite the direction of impact) were observed for large pipeline diameters/internal pressures. For these simulations, the maximum permanent displacement occurred a slight distance away from the impact location. A schematic of this scenario is shown in Fig. 3.

3. RSM development

The expression for a general cubic RSM for an unknown response, Y, in terms of two independent variables (x_1 and x_2) is given by Eq. (1):

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{12} x_1 x_2 + \beta_{22} x_2^2 + \beta_{111} x_1^3 + \beta_{112} x_1^2 x_2 + \beta_{122} x_1 x_2^2 + \beta_{222} x_2^3 + \varepsilon \quad (1)$$

where the β coefficients are unknown model parameters, and ε is an error term assumed to have a normal distribution with a mean of zero and constant variance. The independent variables often represent some physical quantity (*e.g.*, temperature, dimensions) with a defined range that is believed to influence the response under consideration. In order to estimate the unknown model parameters, each independent variable can be assigned a number of discrete values (levels). By sampling the response, Y, at predefined combinations of the independent variables (referred to as treatment combinations), the unknown model parameters can be estimated by using a least squares method. The number and selection of treatment combinations distinguishes the classification of the RSM. For example, if all possible combinations of the independent variables are considered, the RSM is based on a full factorial design. The RSM can then be expressed in terms of parameter estimates, b, by the following relationship:

$$\hat{Y} = b_0 + b_1 x_1 + b_2 x_2 + b_{11} x_1^2 + b_{12} x_1 x_2 + b_{22} x_2^2 + b_{111} x_1^3 + b_{112} x_1^2 x_2 + b_{122} x_1 x_2^2 + b_{222} x_2^3 \quad (2)$$

where $\hat{Y}$ is the estimate of Y. In the preceding development, it is assumed that the independent variables, x_i, are expressed in coded form (nondimensionalized). The range over which the coded independent variables is often taken to be $[-1, 1]$. By nondimensionalizing the actual (uncoded) levels of the independent variables, the parameter estimates are independent of the chosen unit systems. Additionally, the magnitude of a parameter estimate can be used to assess the relative importance of that term to the estimated response. No conclusions of this sort can be drawn from parameter estimates obtained from uncoded levels of the independent variables. However, it becomes more difficult to estimate the influence of higher-order coded parameters since those terms only become significant when all coded parameters are simultaneously near the edges of the design space (*i.e.*, -1, 1). The relationship between coded (x_i) and uncoded (X_i) independent variables can be defined by:

$$x_i = \frac{2X_i - (X_i^{high} + X_i^{low})}{X_i^{high} - X_i^{low}} \quad (3)$$

where X_i^{high} and X_i^{low} are selected such the coded independent variable equals one and negative one, respectively. Once parameter estimates are obtained from a regression analysis, an analysis of variance (ANOVA) can be performed to determine the statistical significance of each parameter estimate. Any insignificant terms can be removed from the RSM in an appropriate manner, and a new regression analysis is performed. This iterative process is typical and is continued until a final RSM is selected.

For this study, two independent variables were considered: the outer diameter of the pipeline (X_1) and the applied internal pressure (X_2). A full factorial statistical design [4] was developed using FE simulation results [1]. Six levels were used for each independent variable resulting in a total of 36 treatment combinations. The individual uncoded and coded levels for both independent variables are given in Table 2. Six RSMs were developed to estimate the maximum permanent deflection, absorbed energy, and maximum impact force when the impact occurred at midspan and one-quarter span locations.

4. Assessment of the RSMs

In order to develop the RSMs for absorbed energy, maximum permanent deflection, and maximum impact force, Statistical Analysis Software (SAS) was used to perform a regression analysis, and an ANOVA was used to determine the significance of model parameter estimates. Linear, quadratic, and cubic RSMs were initially considered to predict the three responses. Quadratic RSMs were determined to provide the best fit to the FE simulation data for all of the responses except one. A full cubic model was used to generate the RSM to characterize the maximum permanent deflection due to a midspan impact. An ***F***-test was performed to determine if the model was statistically significant (P-value $\leq$ 0.05). The R^2-value and adjusted R^2-value were also assessed to determine the quality of the model. A value of unity for the R^2-value and adjusted R^2-value indicates a perfect linear