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MODELLING OF MINING DRAGLINE JOINT: A SENSITIVITY ANALYSIS WITH SOBOL'S VARIANCE-BASED METHOD

Ilyani Akmar Abu Bakar*, Jurina Jaafar, Haryati Awang, Nurathirah Alyun Shamsham Nahar

Faculty of Civil Engineering, Universiti Teknologi MARA (UiTM), 40450 Shah Alam, Selangor Darul Ehsan, Malaysia

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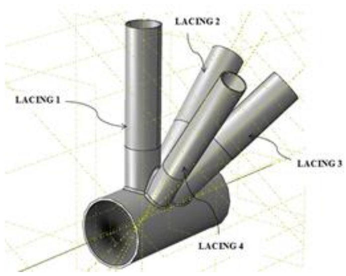
*Corresponding author
ilyan104@salam.uitm.edu.my

Graphical abstract



Abstract

A sensitivity analysis is performed to determine the key uncertain geometric parameters that influence the mechanical response of a mining dragline joint subjected to large dynamic loading. An alternative design is modeled where the welded of the lacing members are attached on the sleeve structure rather than welded to the main chord directly using ABAQUS. Based on the simulated values, the Sobol's variance-based method which consists of first-order and total-effect sensitivity indices is presented. The sensitivity of four uncertain geometric parameters on the mechanical responses are investigated; i.e. thickness of sleeve, thickness of bracing members, weld fillet and eccentricity. To conclude, it is observed that the thickness of sleeve is the most dominant uncertain geometric parameter with respect to the specified mechanical responses.

Keywords: Sensitivity analysis, mining dragline joint, mechanical response, variance-based method

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1.0 INTRODUCTION

Mining involves with extraction of any naturally mineral substances from the earth. Initially, mining done by breaking the ore and loosen it from the rock mass [1]. Dragline [2] is predominantly used in mining through dragging, hoisting and dumping process. Draglines consist of boom with about 100m in length that able to lift bucket of weight more than 100 tonnes [3]. The dragline boom comprises of three tubular main chords that linked together by side bracings/lacings through welding [4-5]. The joints formed between main chords and side bracings/lacings are termed clusters or nodes of dragline boom. The main chords and the bracing/lacing members are placed co-eccentric with each other, see Figure 1. Welding directly the bracing/lacing members to the main chords created a very rigid solid mass at joint node. Joshi *et al*. [7] stated that if some mobility is allowed on the node, stress concentrations will be reduced significantly. Thus, an alternative design with the use of sleeve structure attached to the main chords is introduced to reduce the stress concentration [8], see Figure 2. This sleeve structure is attached to the main chords by cutting the tube longitudinally into halves, welding parallel brackets and fastening with nuts and bolts. It prevents slip between main chords and sleeves by frictional shear stress on the surface [7].

During the execution of dragging, hoisting and dumping processes, the mining draglines are subjected to a large dynamic loading. This dynamic loading induces fractures [9-10], wearings and fatigue failures in the working parts of mining draglines. Sensitivity analysis (SA) [11] studies the influence of an individual or a set of inputs toward the output of interest [12]. The advantage of SA is that the parameters whose uncertainty affects most of the output can be identified by which it can be used to establish experiment (or field) research priorities, leading to a better definition of the unknown parameters. Hence, the uncertainty range can be reduced. The process can be iterated until an acceptable uncertainty range of output is achieved [13]. The present study is mainly focused on sensitivity analysis of mining dragline joint under variance-based sensitivity analysis which quantified the most dominant parameter of uncertainty geometric parameters on the material properties (Von Mises and minimum principal stresses). The uncertainty geometric parameters of interest are the thickness of sleeve, thickness of bracing members, weld fillet and eccentricity.

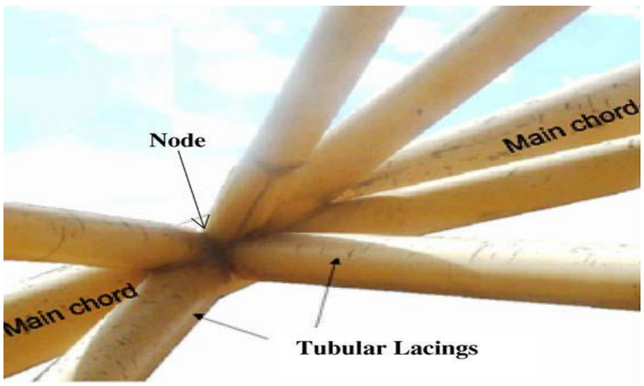

Figure 1 Existing design of dragline boom without sleeve [6]

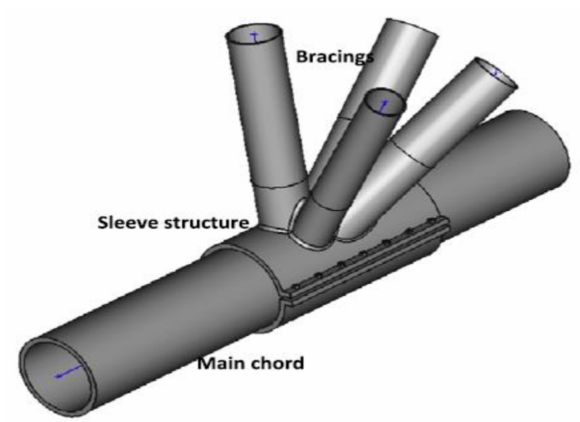

Figure 2 An alternative design of mining dragline with sleeve [7]

2.0 SOBOL'S VARIANCE BASED METHOD

Variance-based sensitivity analysis aims to quantify the amount of variance of each input that contributes to the variance of the model output. These amounts of variances which are caused either by a single parameter or by the interaction of two or more parameters are known as Sobol's sensitivity indices [14-19]. The first-order sensitivity index, S_i indicates a direct variance-based measure of sensitivity. When the number of parameters becomes large, the total-order index S_{Ti} which indicates the sum of all the indices gives an exclusive and residual influence [20]. Interaction effects are when two uncertain parameters interacted with each other and shown effect on output but cannot be expressed as a sum of their single effect. Interactions represent important features of model, and are more difficult to detect than first order [18].

Assume, model output (Y) is a function of input parameters (X_1, X_2, X_3,…., X_q) and can be written as in Eq. 1 [21]

$$Y = f\left(X_1, X_2, X_3, \dots, X_q\right). \quad (1)$$

In Sobol's indices [17-18], total unconditional variance $V(Y)$, could be decomposed into partial variances of increasing dimensionality as in Eq. 2 [21].

$$V(Y) = \sum_i^q V_i + \sum_i^q \sum_{j>i}^q V_{ij} + \dots + V_{12\dots q}\,. \quad (2)$$

where $\sum_i^q V_i$ is the sum of partial variances that includes the main effects of each input parameter, $\sum_i^q \sum_{j>i}^q V_{ij}$ includes all the partial variances of interaction of two input parameters and so on. Dividing the Eq. 3 by total unconditional variance, it becomes [21]

$$\sum_i^q S_i + \sum_i^q \sum_{j>i}^q S_{ij} + \dots + S_{12\dots q} = 1 \quad (3)$$

where $\sum_i^q S_i = \frac{\sum_i^q V_i}{V(Y)}$ is the sum of first order indices, $\sum_i^q \sum_{j>i}^q S_{ij} = \frac{\sum_i^q \sum_{j>i}^q V_{ij}}{V(Y)}$ is the sum of second order indices and so forth. Hence, first order index, S_i and second order index, S_{ij} for each input parameter are given as in Eq. 4 and Eq. 5, respectively [21].

$$S_i = \frac{V_i}{V(Y)} \quad (4)$$

$$S_{ij} = \frac{V_{ij}}{V(Y)} \quad (5)$$

Due to the ratio of partial variances (V_i, V_j) to total variance $V(Y)$, all the sensitivity indices are scaled between 0 to 1 interval. When the summation of all first order gives the value of one, $\sum_i^q S_i$ the model is known as additive which means without interaction effect. Hence, $1 - \sum_i^q S_i$ indicates interaction effects that could either be one or a combination of second order or higher order. The total effect index S_{Ti} for each input parameter is given by Eq. 6 [21].

$$S_{Ti} = S_i + \sum_{i \neq j} S_{ij} + \sum_{i \neq j \neq l} S_{ijl} + \cdots\,. \quad (6)$$

3.0 UNCERTAINTY GEOMETRIC PARAMETERS

The four uncertainty geometric parameters investigated are thickness of sleeve, thicknesses of bracing/lacing members, weld fillet radius and eccentricity [7].

3.1 Thickness of Sleeve

The thickness of the sleeve is varied according to the available pipe size based on ASME/ANSI B36.19M Stainless Steel Pipe [22] with the outer diameter kept fixed. The self-weight of the structure increases with the increases of the thickness of the sleeve. By increasing the sleeve thickness, the excessive stress is reduced due to the wider load paths given for the force to pass through.

3.2 Thicknesses of Bracings/lacings

The dragline joint has four concurrent bracings/lacings wherein one of them is thinner than the other three. The bracings/lacings thicknesses are varied according to ASME/ANSI B36.19M Stainless Steel Pipe [22] with the outer diameter of bracings/lacings are fixed. The self-weight of the structured should be expected to increase with the increasing of bracing/lacing thickness.

3.3 Weld Fillet Radius

The weld fillet radius is varied from 10 mm to 30 mm to capture the entire plausible range. Fillet radius of less than 10 mm is neither practicable nor advisable in the real structure of dragline booms that up to hundred meters. Meanwhile, the fillet radius that extremely large is also unadvisable due to the fact that excessive amount of weld material is applied which increase the self-weight of structure and contributes further to residual stresses at critical locations.

3.4 Eccentricity

The eccentricity is positive when the point of intersection of the bracing/lacing centerlines lies below the axis of the sleeve and vice versa. The positive eccentricity includes the welded node moving below the centerline of sleeve and decreasing the extent of overlapped. Negative eccentricity covers the whole bracings/lacings mass up from the centerline of sleeve and increasing the extent of the sleeve. Eccentricity varied from negative one quarter of outer diameter of sleeve to positive one quarter of the outer diameter of sleeve.

4.0 PROBLEM FORMULATION

The estimation of uncertainty parameters on material properties (minimum principal and Von Mises stresses) of mining dragline joints have been conducted by ABAQUS [23] and simulated in MATLAB. The full model is shown in Figure 3. The stainless steel of density 7800 kg/m^3, Young's modulus of 210 GPa and Poisson's ratio of 0.3 are assigned to the sleeve models. The loads are applied at the cross sectional areas of the extremities of the cylindrical. The boundary conditions are set as fixed at both ends. The combinations of tetrahedral and hexahedral meshes are adopted.

The material properties (Von Mises and minimum principal stresses) are extracted at four critical locations once simulated with ABAQUS, see Figure 4. In MATLAB, the Sobol's variance-based analysis [17-18] is applied on the extracted data using the self-developed codes.

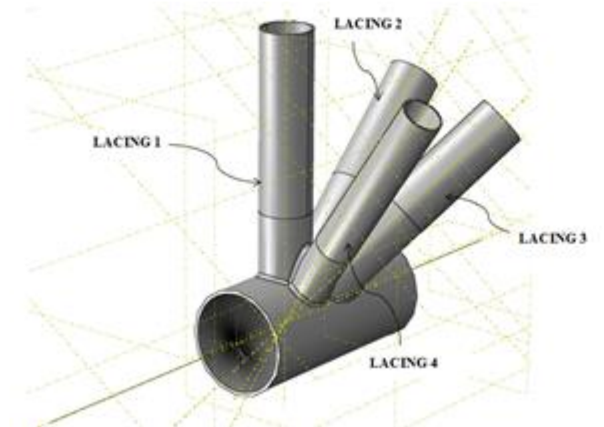

Figure 3 Mining dragline joint model

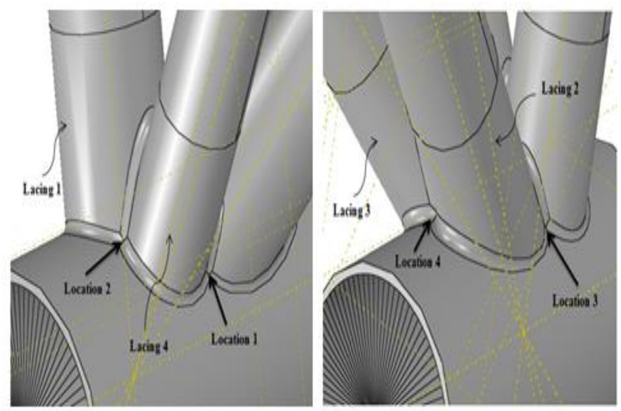

Figure 4 Critical location at weld toes [7]

The Latin Hypercube Sampling [24] is used to compute the full set of first-order and total-effect order for a model of k-factors. For this study, 1000 sampling points are used to get a good estimation of the conditional mean $E(Y|X_i)$ and the procedures are repeated 1000 times to estimate the variances. Explanations for computing the full set of first-order and total-effect indices for a model of k-factors are detailed in [18].

5.0 NUMERICAL RESULTS AND DISCUSSION

The sensitivity analysis is carried out on uncertain geometric parameters of mining dragline joint using Sobol's indices. Table 1 and Table 2 represent the first-order and total-effect sensitivity indices that demonstrate the influences of uncertainty parameters on material properties of dragline joints based on the critical locations which is location 1, location 2, location 3, and location 4, respectively.

The value of total-effect index, $\hat{S}_{Ti}$ which is near to one, indicates the strong relation between one parameter with the others. In contrast, the total-effect index, $\hat{S}_{Ti}$ that approximately zero indicates there is less interaction in between one parameter and another. It could clearly be observed that a strong interaction between the uncertain geometric parameter lies in Von Mises and minimum principal stresses for all regression modes. The differences between $\hat{S}_{Ti}$ and $\hat{S}_{i}$ for both Von Mises and minimum principal stresses are considered small for transverse directions for all four locations. Furthermore, it is found that the thickness of sleeve is the most influential uncertain geometric parameter in Von Mises and minimum principal stresses whilst the least dominant parameter is eccentricity for all four critical locations.

In addition, by varying the thickness of sleeve shows a direct effect on the stresses developed at critical locations in the weldment area. The weld fillet radius becomes the second sensitive variable due to the welding process where the residual stresses are generated. Fundamentally, the residual stress will remain in the structure and combine with the stress result from loading. Unlike the sleeve thickness, the bracing/lacing thicknesses are less sensitive since they carried lesser loadings compared to the sleeve. This is because the bracings/lacings have a minor function in stabilizing the structure against bending and rotation. Since the position of bracing/lacing member is not a major contributor to the stresses, eccentricity became the least influential variable.

The $\hat{S}_1$ value is higher at location 4 due to the point locates between the two bracing/lacing members that diagonal to each other. The diagonal bracing/lacing members increased the extent of the overlap which influenced the value of stresses produced. In contrast, for non-dominance factor, $\hat{S}_4$, the minimum value found at location 1 for minimum principal (see Table 1) and location 2 for Von Mises (see Table 2) which give value of 0.04 and 0.06, respectively. For location 2, one of the bracing/lacing is perpendicular and another one is diagonal thus, the extent of overlap is decreased.

It is also discovered that the value of $\hat{S}_{Ti}$ is greater than $\hat{S}_i$ for all mode of regressions for minimum principal and Von Mises stresses. The presence of interaction in the model could be calculated by $1 - \sum_i S_i$. With the presence of interaction between the uncertainty variable and the output, significantly the value of S_{Ti} will be greater than S_i. The difference, $S_{Ti} - S_i$, is an indicator on the amount of the uncertainty variables involved in interactions with any other uncertainty variables. In addition, it is observed that all of the total-effect indices are less than 1. This shows that the uncertain input variables are non-additive to both stresses. Overall, the dominance of each uncertainty input variable also affected by the location of point, the angle of bracing/lacing members and the size of bracing/lacing members.

The highest sensitivity index is found in full quadratic regression mode for all locations. The reason is due to the higher order mode that is better in precision and accuracy. In addition, the higher order mode is capable to reduce relative error. The rank followed by quadratic with mixed term and linear regression modes.

6.0 CONCLUSION

In this study, the sensitivity analysis has been conducted on uncertain parameters of dragline joints to quantify their sensitivity towards the Von Mises and minimum principal stresses on dragline joints. The sensitivity values obtained were compared based on three regression modes.

The modelling of the mining dragline joint is done using ABAQUS whilst the sensitivity analysis is carried out using Sobol's indices in MATLAB. The Sobol's indices are ratios of partial variances to total variance. Eventually, the sensitivity indices provide a clear idea of the effect of each uncertain parameter onto the variance of the output response. The first-order and total-effect sensitivity indices are estimated in Sobol's variance-based method. The dominant parameter is sleeve thickness since its first-order and total-effect indices are higher compared to other uncertain geometric parameters. In contrast, the non-dominant parameter is found to be eccentricity. Besides, it is concluded that the first-order and total-effect indices are higher in full quadratic regression compared to linear and quadratic without mixed term modes. It is observed that the total-effect indices are less than 1 for all regression modes. This shows that the uncertain input variable is non-additive to both minimum principal and Von Mises stresses.

Conclusively, Sobol's indices provided variation for both single input and the interaction between all the inputs. A reliable result has been obtained through Sobol's variance-based method.

Table 1 First order and total effect sensitivity indices of uncertainty criteria of dragline joint for minimum principal stresses: 1-sleeve thickness; 2-bracing/lacing thickness; 3-weld fillet radius; 4-eccentricity

Material properties	**Minimum principal stresses**		
Location	Linear regression	Quadratic without mixed term	Full quadratic
1	First-order indices, $\hat{S}_i$ $\hat{S}_1 = 0.33$ $\hat{S}_2 = 0.20$ $\hat{S}_3 = 0.20$ $\hat{S}_4 = 0.04$ $\sum_{i=1}^{4} \hat{S}_i = 0.77$	First-order indices, $\hat{S}_i$ $\hat{S}_1 = 0.33$ $\hat{S}_2 = 0.20$ $\hat{S}_3 = 0.21$ $\hat{S}_4 = 0.05$ $\sum_{i=1}^{4} \hat{S}_i = 0.79$	First-order indices, $\hat{S}_i$ $\hat{S}_1 = 0.33$ $\hat{S}_2 = 0.20$ $\hat{S}_3 = 0.23$ $\hat{S}_4 = 0.04$ $\sum_{i=1}^{4} \hat{S}_i = 0.80$
	Total-effect indices, $\hat{S}_{Ti}$ $\hat{S}_{T1} = 0.34$ $\hat{S}_{T2} = 0.20$ $\hat{S}_{T3} = 0.21$ $\hat{S}_{T4} = 0.04$ $\sum_{i=1}^{4} \hat{S}_{Ti} = 0.79$	Total-effect indices, $\hat{S}_{Ti}$ $\hat{S}_{T1} = 0.34$ $\hat{S}_{T2} = 0.20$ $\hat{S}_{T3} = 0.21$ $\hat{S}_{T4} = 0.05$ $\sum_{i=1}^{4} \hat{S}_{Ti} = 0.80$	Total-effect indices, $\hat{S}_{Ti}$ $\hat{S}_{T1} = 0.34$ $\hat{S}_{T2} = 0.20$ $\hat{S}_{T3} = 0.23$ $\hat{S}_{T4} = 0.06$ $\sum_{i=1}^{4} \hat{S}_{Ti} = 0.83$
2	First-order indices, $\hat{S}_i$ $\hat{S}_1 = 0.28$ $\hat{S}_2 = 0.17$ $\hat{S}_3 = 0.20$ $\hat{S}_4 = 0.06$ $\sum_{i=1}^{4} \hat{S}_i = 0.71$	First-order indices, $\hat{S}_i$ $\hat{S}_1 = 0.28$ $\hat{S}_2 = 0.18$ $\hat{S}_3 = 0.20$ $\hat{S}_4 = 0.07$ $\sum_{i=1}^{4} \hat{S}_i = 0.73$	First-order indices, $\hat{S}_i$ $\hat{S}_1 = 0.28$ $\hat{S}_2 = 0.19$ $\hat{S}_3 = 0.21$ $\hat{S}_4 = 0.07$ $\sum_{i=1}^{4} \hat{S}_i = 0.75$
	Total-effect indices, $\hat{S}_{Ti}$ $\hat{S}_{T1} = 0.29$ $\hat{S}_{T2} = 0.18$ $\hat{S}_{T3} = 0.21$ $\hat{S}_{T4} = 0.07$ $\sum_{i=1}^{4} \hat{S}_{Ti} = 0.75$	Total-effect indices, $\hat{S}_{Ti}$ $\hat{S}_{T1} = 0.29$ $\hat{S}_{T2} = 0.20$ $\hat{S}_{T3} = 0.21$ $\hat{S}_{T4} = 0.08$ $\sum_{i=1}^{4} \hat{S}_{Ti} = 0.78$	Total-effect indices, $\hat{S}_{Ti}$ $\hat{S}_{T1} = 0.29$ $\hat{S}_{T2} = 0.21$ $\hat{S}_{T3} = 0.21$ $\hat{S}_{T4} = 0.09$ $\sum_{i=1}^{4} \hat{S}_{Ti} = 0.80$
3	First-order indices, $\hat{S}_i$ $\hat{S}_1 = 0.25$ $\hat{S}_2 = 0.17$ $\hat{S}_3 = 0.21$ $\hat{S}_4 = 0.05$ $\sum_{i=1}^{4} \hat{S}_i = 0.68$	First-order indices, $\hat{S}_i$ $\hat{S}_1 = 0.25$ $\hat{S}_2 = 0.17$ $\hat{S}_3 = 0.21$ $\hat{S}_4 = 0.06$ $\sum_{i=1}^{4} \hat{S}_i = 0.69$	First-order indices, $\hat{S}_i$ $\hat{S}_1 = 0.26$ $\hat{S}_2 = 0.18$ $\hat{S}_3 = 0.21$ $\hat{S}_4 = 0.06$ $\sum_{i=1}^{4} \hat{S}_i = 0.71$
	Total-effect indices, $\hat{S}_{Ti}$ $\hat{S}_{T1} = 0.26$ $\hat{S}_{T2} = 0.18$ $\hat{S}_{T3} = 0.20$ $\hat{S}_{T4} = 0.06$ $\sum_{i=1}^{4} \hat{S}_{Ti} = 0.70$	Total-effect indices, $\hat{S}_{Ti}$ $\hat{S}_{T1} = 0.26$ $\hat{S}_{T2} = 0.18$ $\hat{S}_{T3} = 0.20$ $\hat{S}_{T4} = 0.06$ $\sum_{i=1}^{4} \hat{S}_{Ti} = 0.70$	Total-effect indices, $\hat{S}_{Ti}$ $\hat{S}_{T1} = 0.27$ $\hat{S}_{T2} = 0.19$ $\hat{S}_{T3} = 0.22$ $\hat{S}_{T4} = 0.06$ $\sum_{i=1}^{4} \hat{S}_{Ti} = 0.74$

4	First-order indices, $\hat{S}_i$ $\hat{S}_1 = 0.33$ $\hat{S}_2 = 0.20$ $\hat{S}_3 = 0.24$ $\hat{S}_4 = 0.05$ $\sum_{i=1}^{4} \hat{S}_i = 0.82$ Total-effect indices, $\hat{S}_{Ti}$ $\hat{S}_{T1} = 0.35$ $\hat{S}_{T2} = 0.21$ $\hat{S}_{T3} = 0.24$ $\hat{S}_{T4} = 0.06$ $\sum_{i=1}^{4} \hat{S}_{Ti} = 0.85$	First-order indices, $\hat{S}_i$ $\hat{S}_1 = 0.34$ $\hat{S}_2 = 0.20$ $\hat{S}_3 = 0.24$ $\hat{S}_4 = 0.05$ $\sum_{i=1}^{4} \hat{S}_i = 0.83$ Total-effect indices, $\hat{S}_{Ti}$ $\hat{S}_{T1} = 0.35$ $\hat{S}_{T2} = 0.21$ $\hat{S}_{T3} = 0.25$ $\hat{S}_{T4} = 0.06$ $\sum_{i=1}^{4} \hat{S}_{Ti} = 0.87$	First-order indices, $\hat{S}_i$ $\hat{S}_1 = 0.34$ $\hat{S}_2 = 0.21$ $\hat{S}_3 = 0.24$ $\hat{S}_4 = 0.05$ $\sum_{i=1}^{4} \hat{S}_i = 0.84$ Total-effect indices, $\hat{S}_{Ti}$ $\hat{S}_{T1} = 0.35$ $\hat{S}_{T2} = 0.22$ $\hat{S}_{T3} = 0.25$ $\hat{S}_{T4} = 0.06$ $\sum_{i=1}^{4} \hat{S}_{Ti} = 0.88$

Table 2 First order and total effect sensitivity indices of uncertainty criteria of dragline joint for Von Mises stresses: 1-sleeve thickness; 2-bracing/lacing thickness; 3-weld fillet radius; 4-eccentricity

Material properties		**Von Mises stresses**	
Location	Linear regression	Quadratic without mixed term	Full quadratic
1	First-order indices, $\hat{S}_i$ $\hat{S}_1 = 0.33$ $\hat{S}_2 = 0.16$ $\hat{S}_3 = 0.23$ $\hat{S}_4 = 0.07$ $\sum_{i=1}^{4} \hat{S}_i = 0.79$ Total-effect indices, $\hat{S}_{Ti}$ $\hat{S}_{T1} = 0.35$ $\hat{S}_{T2} = 0.17$ $\hat{S}_{T3} = 0.23$ $\hat{S}_{T4} = 0.07$ $\sum_{i=1}^{4} \hat{S}_{Ti} = 0.82$	First-order indices, $\hat{S}_i$ $\hat{S}_1 = 0.33$ $\hat{S}_2 = 0.18$ $\hat{S}_3 = 0.23$ $\hat{S}_4 = 0.07$ $\sum_{i=1}^{4} \hat{S}_i = 0.81$ Total-effect indices, $\hat{S}_{Ti}$ $\hat{S}_{T1} = 0.35$ $\hat{S}_{T2} = 0.18$ $\hat{S}_{T3} = 0.24$ $\hat{S}_{T4} = 0.07$ $\sum_{i=1}^{4} \hat{S}_{Ti} = 0.84$	First-order indices, $\hat{S}_i$ $\hat{S}_1 = 0.33$ $\hat{S}_2 = 0.19$ $\hat{S}_3 = 0.25$ $\hat{S}_4 = 0.07$ $\sum_{i=1}^{4} \hat{S}_i = 0.84$ Total-effect indices, $\hat{S}_{Ti}$ $\hat{S}_{T1} = 0.35$ $\hat{S}_{T2} = 0.20$ $\hat{S}_{T3} = 0.25$ $\hat{S}_{T4} = 0.07$ $\sum_{i=1}^{4} \hat{S}_{Ti} = 0.87$
2	First-order indices, $\hat{S}_i$ $\hat{S}_1 = 0.28$ $\hat{S}_2 = 0.16$ $\hat{S}_3 = 0.23$ $\hat{S}_4 = 0.06$ $\sum_{i=1}^{4} \hat{S}_i = 0.73$ Total-effect indices, $\hat{S}_{Ti}$ $\hat{S}_{T1} = 0.30$ $\hat{S}_{T2} = 0.17$ $\hat{S}_{T3} = 0.23$ $\hat{S}_{T4} = 0.07$ $\sum_{i=1}^{4} \hat{S}_{Ti} = 0.77$	First-order indices, $\hat{S}_i$ $\hat{S}_1 = 0.29$ $\hat{S}_2 = 0.16$ $\hat{S}_3 = 0.24$ $\hat{S}_4 = 0.07$ $\sum_{i=1}^{4} \hat{S}_i = 0.76$ Total effect-indices, $\hat{S}_{Ti}$ $\hat{S}_{T1} = 0.30$ $\hat{S}_{T2} = 0.18$ $\hat{S}_{T3} = 0.24$ $\hat{S}_{T4} = 0.07$ $\sum_{i=1}^{4} \hat{S}_{Ti} = 0.79$	First-order indices, $\hat{S}_i$ $\hat{S}_1 = 0.29$ $\hat{S}_2 = 0.17$ $\hat{S}_3 = 0.24$ $\hat{S}_4 = 0.07$ $\sum_{i=1}^{4} \hat{S}_i = 0.77$ Total-effect indices, $\hat{S}_{Ti}$ $\hat{S}_{T1} = 0.31$ $\hat{S}_{T2} = 0.18$ $\hat{S}_{T3} = 0.25$ $\hat{S}_{T4} = 0.08$ $\sum_{i=1}^{4} \hat{S}_{Ti} = 0.82$

3	First-order indices, $\hat{S}_i$ $\hat{S}_1 = 0.28$ $\hat{S}_2 = 0.16$ $\hat{S}_3 = 0.22$ $\hat{S}_4 = 0.07$ $\sum_{i=1}^{4} \hat{S}_i = 0.73$ Total-effect indices, $\hat{S}_{Ti}$ $\hat{S}_{T1} = 0.29$ $\hat{S}_{T2} = 0.18$ $\hat{S}_{T3} = 0.23$ $\hat{S}_{T4} = 0.08$ $\sum_{i=1}^{4} \hat{S}_{Ti} = 0.78$	First-order indices, $\hat{S}_i$ $\hat{S}_1 = 0.29$ $\hat{S}_2 = 0.15$ $\hat{S}_3 = 0.23$ $\hat{S}_4 = 0.08$ $\sum_{i=1}^{4} \hat{S}_i = 0.75$ Total-effect indices, $\hat{S}_{Ti}$ $\hat{S}_{T1} = 0.30$ $\hat{S}_{T2} = 0.18$ $\hat{S}_{T3} = 0.23$ $\hat{S}_{T4} = 0.08$ $\sum_{i=1}^{4} \hat{S}_{Ti} = 0.79$	First-order indices, $\hat{S}_i$ $\hat{S}_1 = 0.29$ $\hat{S}_2 = 0.17$ $\hat{S}_3 = 0.23$ $\hat{S}_4 = 0.09$ $\sum_{i=1}^{4} \hat{S}_i = 0.78$ Total-effect indices, $\hat{S}_{Ti}$ $\hat{S}_{T1} = 0.30$ $\hat{S}_{T2} = 0.19$ $\hat{S}_{T3} = 0.24$ $\hat{S}_{T4} = 0.09$ $\sum_{i=1}^{4} \hat{S}_{Ti} = 0.82$
4	First-order indices, $\hat{S}_i$ $\hat{S}_1 = 0.35$ $\hat{S}_2 = 0.18$ $\hat{S}_3 = 0.19$ $\hat{S}_4 = 0.08$ $\sum_{i=1}^{4} \hat{S}_i = 0.80$ Total-effect indices, $\hat{S}_{Ti}$ $\hat{S}_{T1} = 0.36$ $\hat{S}_{T2} = 0.21$ $\hat{S}_{T3} = 0.21$ $\hat{S}_{T4} = 0.08$ $\sum_{i=1}^{4} \hat{S}_{Ti} = 0.86$	First-order indices, $\hat{S}_i$ $\hat{S}_1 = 0.36$ $\hat{S}_2 = 0.19$ $\hat{S}_3 = 0.20$ $\hat{S}_4 = 0.08$ $\sum_{i=1}^{4} \hat{S}_i = 0.83$ Total-effect indices, $\hat{S}_{Ti}$ $\hat{S}_{T1} = 0.37$ $\hat{S}_{T2} = 0.20$ $\hat{S}_{T3} = 0.22$ $\hat{S}_{T4} = 0.09$ $\sum_{i=1}^{4} \hat{S}_{Ti} = 0.88$	First-order indices, $\hat{S}_i$ $\hat{S}_1 = 0.36$ $\hat{S}_2 = 0.20$ $\hat{S}_3 = 0.21$ $\hat{S}_4 = 0.08$ $\sum_{i=1}^{4} \hat{S}_i = 0.85$ Total-effect indices, $\hat{S}_{Ti}$ $\hat{S}_{T1} = 0.37$ $\hat{S}_{T2} = 0.21$ $\hat{S}_{T3} = 0.22$ $\hat{S}_{T4} = 0.09$ $\sum_{i=1}^{4} \hat{S}_{Ti} = 0.89$

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