Modelling the Effect of Pre-Load in a Lap-Joint by Altering Thin Layer Material Properties

Nidhal Jamia[1], Hassan Jalali[2], Michael I. Friswell[1], Hamed Haddad Khodaparast[1] and Javad Taghipour[1]

[1]Faculty of Science and Engineering,
Swansea University, Swansea, SA1 8EN, U.K.

[2]Department of Mechanical & Construction Engineering, Northumbria University
Newcastle upon Tyne, NE1 8ST, U.K.

ABSTRACT

The joints in an assembled structure represent a significant source of energy dissipation and may lead to overall stiffness variation, which may affect high cycle fatigue failure. Many approaches have been developed to model and simulate the dynamics of bolted joint structures. However, the inherent dynamics of the contact interfaces still need further investigation in order to be able to generate accurate models to predict the behaviour in the contact interface. In this paper, the modelling of the contact interface of a bolted lap-joint and the prediction of its pressure distribution are considered using 2D and 3D FE models. A 3D finite element model with solid elements is developed to simulate the behaviour of the contact interface. The model is a modified thin-layer element where the material properties of a thin layer are distributed over the contact interface. Due to the high computational cost of the 3D model, a reduced-order model is proposed for the lap-joint in which beam elements are used. The material properties are introduced in these models to account for the variability in the contact parameters. Finally, experimental modal properties were used to identify the joint parameters. A good agreement is obtained between the detailed model and the reduced order model in the prediction of the pressure distribution in the contact interface.

Keywords: Pressure distribution, Bolted lap-joint, Detailed model, Modified thin-layer element, Joint parameters.

INTRODUCTION

In almost all practical mechanical structures, there is at least one mechanical joint. After more than half century of efforts on modelling the hysteretic behaviour of jointed structures, it is still one of the most complicated tasks in structural dynamics. Modelling and investigating the behaviour of mechanical joints have received considerable attention. These efforts have been intensified during recent decades due to progress in computational tools and experimental equipment. Bograd et al. [1] reviewed various identification approaches developed to model the dynamics of mechanical joints.

Iwan [2] presented a model to investigate the yielding behaviour of continuous and composite materials and structures by complementing and extending some of the earliest works [3-7]. Iwan models are capable of predicting both transient and steady-state yielding behaviour of jointed structures. The Iwan model is one of the most important mathematical formulations introduced to predict the dynamic behaviour of joint contact interfaces. Ref. [8] gives an overview of the Iwan model for mechanical jointed structures and presents a reduced order model to investigate the qualitative properties of such systems using a small number of parameters. Many research works have been carried out based on this model. Segalman and Starr [9] compared various constitutive models of joints and discussed how the Iwan model can represent the properties of Massing models. Segalman [10] and Li and Hao [11] developed a four-parameter Iwan-model and a six-parameter Iwan model respectively to investigate the dynamic response of lap-jointed structures. Quinn and Segalman [12] investigated the applicability and performance of the series-series Iwan model in predicting the dynamics of jointed structures.

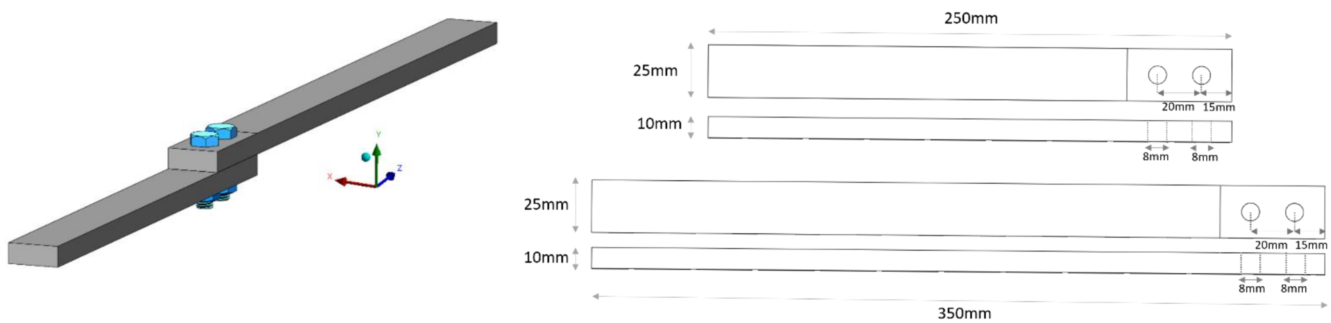
There are various identification methods introduced in the literature for modelling the dynamic behaviour of jointed structures, [13-17]. Ahmadian and Jalali [13] suggested modelling the dynamics of bolted lap-joints by introducing a nonlinear generic element formulation. In [14], Ahamdian and Jalali proposed a nonlinear mathematical model for bolted lap-joints to predict the micro-slip/slap behaviour in the joint contact interface. Noel et al. [15] introduced a nonlinear state-space identification approach to estimate the hysteresis dynamics. Miller and Quinn [16] developed a two-sided interface model using a series-series Iwan model and an elastic chain to predict the dynamic behaviour of structures with frictional joints. They also developed a reduced-order model of the presented approach in order to reduce the computational costs of the modelling. Jalali et al. [18] showed the application of the force-state mapping technique in the identification of nonlinear lap-jointed structures.

Thin layer element theory is another method introduced by Desai et al. [19] to model the contact interface of jointed structures. By carrying out a parametric study, they illustrated that the ratio of the thickness of the thin-layer element to the mean dimension of the adjacent elements should be between 0.01 and 0.1. Jalali et al. [20] exploited thin layer element theory to model the dynamics of bolted lap-joints experiencing micro-slip/slap behaviour. Ehrlich et al. [21] reduced the computational costs and calculation time required for model updating and uncertainty analysis using thin-layer element theory, by proposing a reduced-order model of the thin-layer element theory. Wang et al. [22] developed a parametric modelling approach, based on the finite element method and thin-layer element theory, to estimate the parameters of jointed structures. Iranzad and Ahmadian [23] modelled the dynamics of a lap-type mechanical joint using thin-layer element theory and utilizing experimentally measured data. Zhan et al. [24] focused on modelling and estimating the parameters of the dynamics of bolted joint structures. To this end, they utilized thin-layer elements to model the joint contact interface and exploited three-dimensional brick elements to model the sub-structures of the joint.

This paper investigates modelling the dynamics of a bolted lap-joint utilizing a detailed three-dimensional model and a two-dimensional equivalent beam model. In both models, a modified thin-layer element approach is used to model the joint contact interface where the material properties of the thin layer are considered to be variable over the contact interface. The variable material properties resemble the distribution of the normal contact pressure in the contact interface. Impact modal testing was employed to obtain the measured natural frequencies of the lap-joint. A 3D detailed model and a 2D equivalent model are created using the thin layer approach. An identification of the model parameters is employed using the experimental modal properties of the lap-joint obtained by modal testing.

EXPERIMENTAL ANALYSIS OF LAP-JOINT

In this section, modal testing is performed on a lap-joint structure in order to obtain the undamped natural frequencies, which will be used for the identification of the joint parameters in the next sections. Two different beams with two different lengths joined by two M8 bolts were designed and fabricated in order to compose a lap-joint structure. The design and dimension of the two beams are shown in Figure 1.



(a) (b)

Figure 1: The lap joint: (a) Design (b) Dimensions

The beams are made of structural steel with the following material properties, E = 208 GPa, ρ = 7860 kg/m^3 and υ = 0.3, where E is the Young's modulus, ρ is the density and υ is Poisson's ratio. In order to obtain the natural frequencies of the lap-joint, an impact hammer experiment was performed. In this experiment, a 4-channel (DAQ) system, an impact hammer and data acquisition software were used. In the modal testing procedure, care has been taken to keep the uncertainties to a minimum.

Two identical M8 bolts and nuts are used to join the two beams and a KTC Digital Ratchet Torque Wrench was used to tighten the bolts to a specific level corresponding to a torque level equal to 23 Nm. Free-free boundary conditions were used for the lap-joint structure by suspending it using flexible strings as shown in Figure 2.

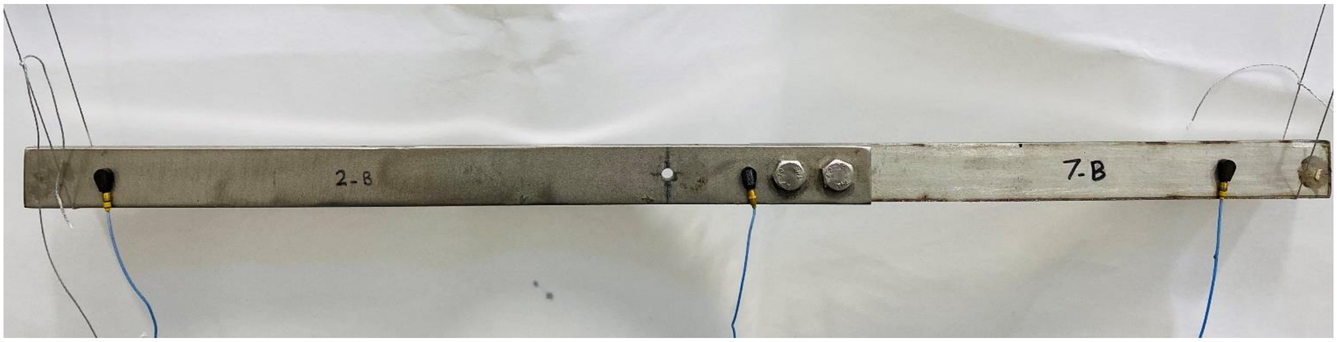


Figure 2: Impact test of a free-free lap-joint

In addition, three miniature PCB accelerometers with 0.5g mass,10kHz frequency range and 10mg/s^2 sensitivity, were bonded to the middle and the two extremities of the beams were used to measure the response of the structure. The details of the experimental setup are presented in Figure 2. The measured natural frequencies are tabulated in Table 1 and they are used in the next sections to identify the joint parameters. In this study, the bending behaviour of the lap-joint structure is of interest. Therefore, the first 8 bending modes, and their corresponding natural frequencies are considered and will be used in the identification of the joint structure in the rest of this study.

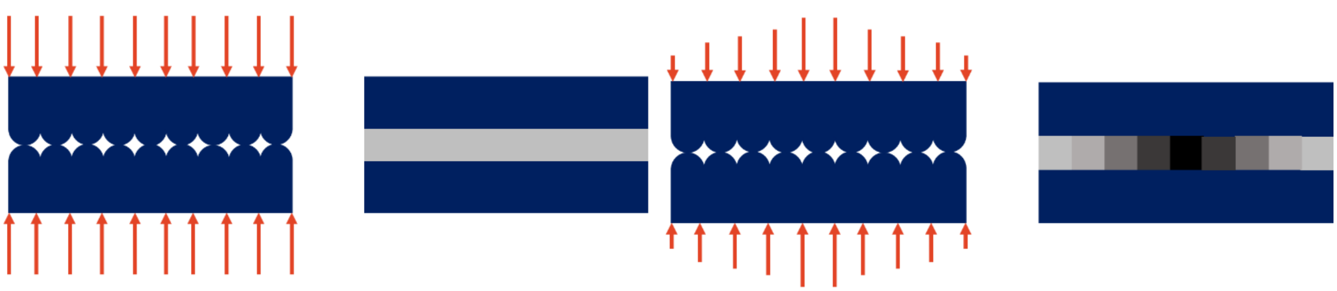
Table 1: Measured natural frequencies for the first 8 bending modes

Mode No.	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8
Exp. (Hz)	158.41	442.81	860.93	1383.5	2045.7	2869.4	3438.9	4279.7

THE MODIFIED THIN LAYER APPROACH

The force-displacement behaviour of a contact interface in the normal and tangential directions is characterized by the condition of the contact surface and the level of the bolt pre-load. For instance, by increasing the bolt pre-load, the linear stiffness of the contact interface in the tangential direction increases. The other parameter which has a direct effect on the force-displacement behaviour is the size of asperities or the contact surface roughness characteristics. Both bolt preload and contact surface roughness are variable over the contact interface: the former has a deterministic nature and the later has a stochastic nature.

In the conventional thin layer approach, equivalent constant material properties are considered for the layer representing the contact interface, as shown in Figure 3(a). The constant material properties are the result of this assumption that both the contact pressure and surface roughness have constant distributions.



(a) (b)

Figure 3: Conventional (a) and modified (b) thin layer approach

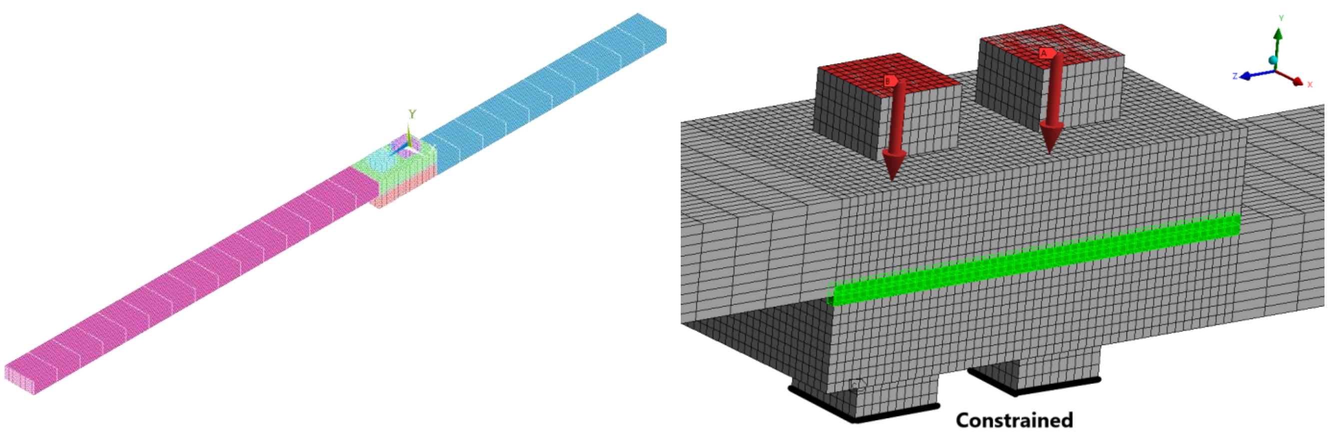
In an attempt to consider the variation of the contact pressure on the thin layer characteristics, in this paper, the distribution of material properties shown in Figure 3(b) is considered for the thin layer. The applicability of this approach is examined using 3D and 2D models of the lap-joint structure shown in Figure 2.

3D DETAILED MODEL

In this section, a detailed 3D FE model of the lap-joint using the thin layer approach is developed. The commercial software ANSYS Workbench is used to perform the FEM analysis.

Two rectangular beams in contact with each other, as shown in Figure 4(a), are considered. For simplicity, four cubes are employed to present the mass of the bolt heads and the nuts. The model geometry details are shown in Figure 4(a). Structural steel with the same parameters as the real lap-joint was assigned as the material for the whole model. The dimensions of the model geometry are given in Figure 1(b). The FE model was constructed using a fine mesh in the contact parts, as shown in Figure 4(b). To provide a high accuracy in the contact interface, particular care was taken to ensure that the pairs of nodes on the two contact surfaces are coincident to ensure an accurate interface mesh. Tetrahedral solid elements were used in the mesh as shown in Figure 4(b). The assembly has 57000 elements and 65070 nodes.

The main approach in this paper is based on an identification process of the material distribution in the thin layer in order to simulate a bolted joint interface under the bolts' preload. The difficulty raised here is the initial 'guess' of the material properties distribution in the contact interface in order to identify the final state of the material properties distribution. An assumption is made in this paper where the material properties in the contact interface behave similarly to the normal stress distribution in the thin layer.



(a) (b)

Figure 4: (a) Detailed model of the lap-joint (b) Thin layer

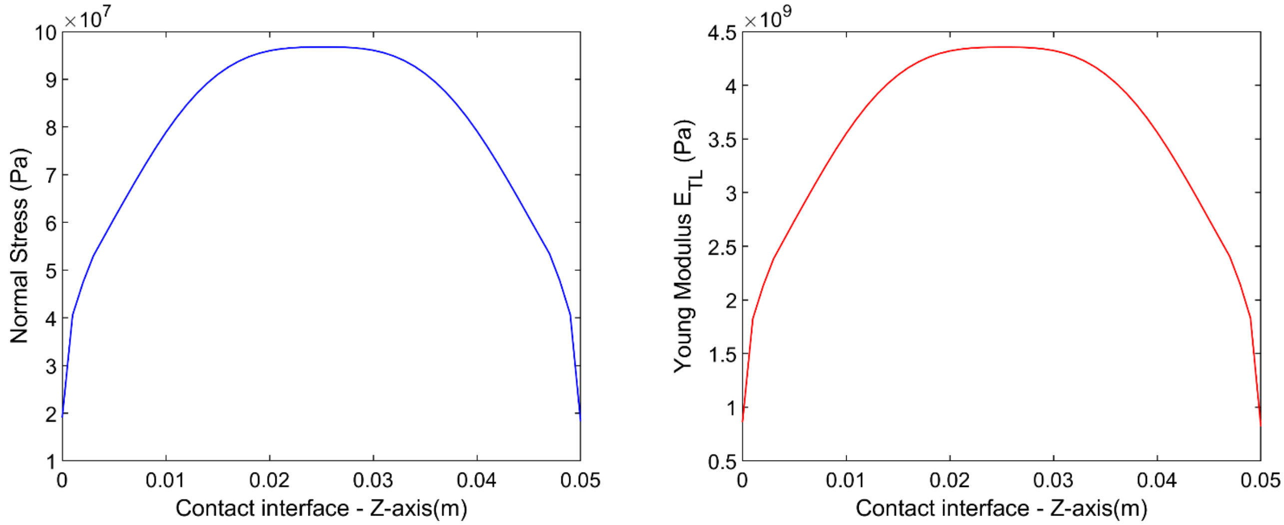
At the first stage, a thin layer with thickness equal to 2 mm is selected by selecting all the elements that are located in the contact interface. A constant Young's modulus E_{TL} is assigned to the thin layer. The bottom surfaces of the two cubes presenting the nuts are constrained as shown in Figure 4(b). A force F_b is applied to the two upper cubes. This force presents the preload of the bolts (e.g. bolt pretensions). A static analysis is first performed to obtain the prestressed structure. This structure is then employed in a prestressed modal analysis to account for the effects of the applied force and the thin layer stiffness on the natural frequencies of the structure.

At the second stage, the natural frequencies are calculated at each set of the Young's modulus E_{TL} and the applied force F_b. The two values of E_{TL} and F_b are identified by minimizing the difference between the measured and the simulated natural frequencies for the first eight bending modes. This operation is performed using the minimization function 'fminsearch' in MATLAB. The identified values are E_{TL} = 1.262815928GPa and F_b = -92.977kN. The identified natural frequencies and the accuracy of the identified model parameters are reported in Table 2 for the experimental results corresponding to the first 8 bending modes.

Table 2: Accuracy of the identified E_{TL} and F_b for the first 8 bending modes (3D model)

Mode No.	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8
Exp. (Hz)	158.41	442.81	860.93	1383.5	2045.7	2869.4	3438.9	4279.7
Simulated (Hz)	157.22	448.08	886.59	1455.04	2061.75	2950.9	3137.32	4205.32
Error (%)	0.75	1.17	2.89	4.91	0.77	2.76	9.6	1.76

After identifying E_{TL} and F_b, a static analysis is performed using these two values to obtain the distribution of the normal stress at the contact interface, as shown in Figure 5(a). Assuming that the material properties distribution in the thin layer is behaving as the distribution of the normal stress in the contact interface, the material properties distribution given in Figure 5(b) is generated from the results shown in Figure 5(a).



(a) (b)

Figure 5: (a) Normal stress distribution in the contact interface (b) Material properties distribution in the thin layer

Finally, to verify the assumption considered in this study, the obtained material properties distribution is employed in a modal analysis of the free-free case and the natural frequencies of the first 8 bending modes are calculated. The accuracy of the obtained results is shown in Table 3.

Table 3: Accuracy of the identified material properties distribution for the first 8 bending modes (3D model)

Mode No.	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8
Exp. (Hz)	158.41	442.81	860.93	1383.5	2045.7	2869.4	3438.9	4279.7
Simulated (Hz)	158.32	460.77	900.4	1434.93	2058	2997.34	3230.84	4348.43
Error (%)	0.056	4.05	4.58	3.71	0.6	4.45	6.05	1.6

As shown in Table 3, the simulated natural frequencies are accurate for 4 modes. For the rest of the modes, the error is around 4% which can be reduced by using a more robust minimization algorithm, specifically that the identification in this study is performed over 8 modes. Decreasing the number of modes identified might increase the accuracy.

2D EQIVALENT MODEL

The same procedure as for the 3D case described in the previous section is followed for a 2D model of the beam structure shown in Figure 2. Figure 6 shows the 2D FE model where the contact interface is modelled as a thin layer.

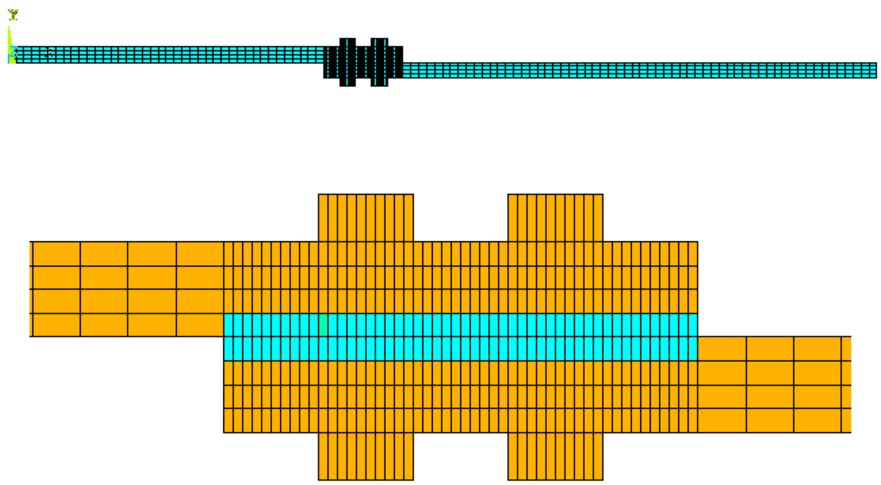


Figure 6: The 2D FE model

The identified distribution of the material properties, i.e. E, in the contact interface is shown in Figure 7 and Table 4 shows the comparison between the experimental and the identified natural frequencies.

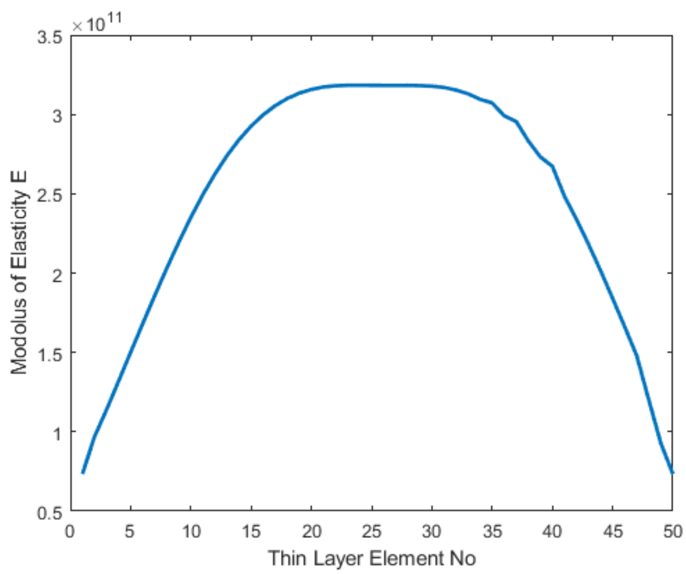


Figure 7: Identified distribution of the material properties in the thin layer using the 2D model

Table 4: Accuracy of the identified material properties distribution for the first 8 bending modes (2D model)

Mode No.	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8
Exp. (Hz)	158.41	442.81	860.93	1383.5	2045.7	2869.4	3438.9	4279.7
Simulated (Hz)	160.57	433.67	885.2	1424.3	2066.4	2980.4	3355.6	4296.1
Error (%)	1.36	2.45	2.81	2.80	1.01	3.87	-2.42	0.38

The results presented in these tables show that the method presented in this paper is able to model the effect of preload on contact interface.

CONCLUSION

In this paper 2D and 3D FE models were constructed to simulate a bolted lap-joint. The thin layer approach was employed to simulate the contact interface of the joint structure. An identification of the joint model parameters was performed using the measured and simulated natural frequencies of the bending modes. The accuracy of the results showed that the material properties distribution in the thin layer can be generated from the normal stress distribution in the contact interface. This work showed a good agreement of the two models to predict the pressure distribution in the contact interface. This approach will be extended to stochastic modelling by considering a stochastic thin layer in the contact interface.

ACKNOWLEDGEMENTS

This research is funded by the Engineering and Physical Sciences Research Council through Grant no. EP/R006768/1. Javad Taghipour acknowledges financial support from the College of Engineering at Swansea University through the PhD scholarship in support of EPSRC project EP/P01271X/1.

REFERENCES

[1] S. Bograd, P. Reuss, A. Schmidt, L. Gaul, M. Mayer, Modeling the dynamics of mechanical joints, Mechanical Systems and Signal Processing 25 (2011) 2801–2826.

[2] W.D. Iwan, “On a class of models for the yielding behavior of continuous composite systems”, Journal of Applied Mechanics, 89, 1967, pp. 612-617.

[3] Massing, G., "Eigenspannungen und Verfestigung beim Messing," Proceedings of the Second International Congress of Applied Mechanics, 1926, pp. 332-335.

[4] Duwez, P., "On the Plasticitv of Crystals," Physical Review, Vol. 47, 1935, pp. 494-501.

[5] D.C. Drucker, "On the Continuum as an Assemblage of Homogeneous Elements or States," Brown University Technical Report No. 50,1966.

[6] D.E. Ivlev, "The Theory of Complex Media," Soviet Physics—Doklady, Vol.8, No. 1, July 1963, pp. 28-30.

[7] W. Prager, "Models of Plastic Behavior," Proceedings of the Fifth U. S. ATational Congress of Applied Mechanics, ASME, 1966, pp. 447-448.

[8] D.J. Segalman, An Initial Overview of Iwan Modeling for Mechanical Joints, SAND2001-0811 Unlimited Release March 2001.

[9] D.J. Segalman, M.J. Starr, Relationships Among Certain Joint Constitutive Models, SAND2004-4321, Unlimited Release, Printed September 2004.

[10] D.J. Segalman, A Four-Parameter Iwan Model for Lap-Type Joints, Transactions of the ASME, Vol. 72, SEPTEMBER 2005, pp. 752-760.

[11] Y. Li, Z. Hao, A six-parameter Iwan model and its application, Mechanical systems and Signal Processing 68-69 (2016) 354–365.

[12] D.D. Quinn, D.J. Segalman, Using Series-Series Iwan-Type Models for Understanding Joint Dynamics, Transactions of the ASME, Vol. 72, SEPTEMBER 2005, pp. 666-673.

[13] H. Ahmadian, H. Jalali, Identification of bolted lap joints parameters in assembled structures, Mechanical Systems and Signal Processing 21 (2007) 1041–1050.

[14] H. Ahmadian, H. Jalali, Generic element formulation for modelling bolted lap joints, Mechanical Systems and Signal Processing 21 (2007) 2318–2334.

[15] J.D. Miller, D.D. Quinn, A two-sided interface model for dissipation in structural systems with frictional joints, Journal of Sound and Vibration 321 (2009) 201–219.

[16] J.P.Noël, A.F.Esfahani, G.Kerschen, J.Schoukens, A nonlinear state-space approach to hysteresis identification, Mechanical Systems and Signal Processing 84 (2017) 171–184.

[17] T. Naraghi, A.S. Nobari, A novel method for the identification of a model for the nonlinear characteristic of a bolted lap-joint, Journal of Vibration and Control, 2017, Vol. 23(3) 484–500.

[18] H. Jalali, H. Ahmadian, J.E. Mottershead, Identification of nonlinear bolted lap-joint parameters by force-state mapping, International Journal of Solids and Structures 44 (2007) 8087–8105.

[19] C.S. Desai, M.M. Zaman, J.G. Lightner, H.J. Siriwardane, Thin-Layer Element for Interfaces and Joints, International Journal For Numerical And Analytical Methods In Geomechanics. Vol. 8. 1943 (1984).
[20] H. Jalali, A. Hedayati, H. Ahmadian, Modelling mechanical interfaces experiencing micro-slip/slap, Inverse Problems in Science and Engineering, Vol. 19, No. 6, September 2011, 751–764.
[21] C. Ehrlich, A. Schmidt, L. Gaul, Reduced thin-layer elements for modeling the nonlinear transfer behavior of bolted joints of automotive engine structures, Arch Appl Mech (2016) 86:59–64.
[22] Z. Wang, C.W. Fei, J.J. Wang, Equivalent simulation of mechanical characteristics for parametric modeling of bolted joint structures, Advances in Mechanical Engineering, 2017, Vol. 9(6) 1–12.
[23] M. Iranzad, H. Ahmadian, Identification of nonlinear bolted lap joint models, Computers and Structures 96-97 (2012) 1–8.
[24] M. Zhan, Q. Guo, L. Yue, B. Zhang, Modeling and Stochastic Model Updating of Bolt-Jointed Structure, Shock and Vibration, Volume 2018, Article ID 8354249.