Identification of Joint Interface Models

H.Ahmadian A.Najafi-Amin
Iran University of Science & Technology
Narmak,Teheran,16844,IRAN
ahmadian@iust.ac.ir

J.E.Mottershead S.James
University of Liverpool
Liverpool,L69 3GH,UK
j.e.mottershead@liv.ac.uk

M.I.Friswell
University of Wales
Swansea,SA2 8PP,UK
m.i.friswell@swan.ac.uk

Abstract: This paper develops linear dynamic models for joints and interfaces that can be incorporated into existing commercial finite element codes. It is critical to determine only the simplest model possible which also captures the behavior of dominant physics of the joint. The parameters related to the dominant physics are identified using experimentally measured data. The goal is to develop guidelines in designing models for joints and interfaces. This work provides insight to the analyst on to how the model should be designed in the joint region.

1 Introduction

The behavior of joints in mechanical structures significantly affects their dynamic response. A structure consist primarily of linear substructures connected by joints of various sorts. These joints present considerable uncertainty in the modelling because of the complicated and nonlinear physics involved in them. Determining the relevant physics on each joint is critical to a validated full body model of the structure. Modelling of joints has been investigated by many researchers [1-9]. The three most common mechanisms of joint mechanics are frictional slip at bolted or face-to-face compression joints, slapping at gaps, and reflection/transmission at locations of mismatch of mechanical impedance. All three postulated mechanisms have their own characteristic features. For instance frictional slip becomes saturated at very high amplitudes and slapping pushes energy from low to high frequencies.

We intend to develop linear dynamic models for joints that can be incorporated into existing commercial finite element codes. It is critical to determine only the simplest model possible which also captures the behavior of the dominant physics of the joint. Even with the fast computers available today, micromechanics are not amenable to full system models. An appropriate system to attempt to model is the MACE (Modal Analysis Coupling Experiment) structure [10]. The MACE structure has been built by AWE and is developed with the intent of being an unclassified warhead-like structure with joints and substructures as would be found in a typical warhead. This makes an ideal starting place for a joint study.

In this work, we determine the relevant physics that characterizes the joint. The dynamics of these joints, including threaded, and face-to-face contact joints, present difficulties in modelling the associated physics. We propose a combined experimental and analytic approach where the experiments are driven by the uncertainties in the model. Modal testing techniques are used to compare experimental results to model predictions, and to isolate the differences. Differences between the experiment and the analysis will be studied through simplified models. While there are many active mechanisms in the joint, this work will try to identify the dominant ones. The goal is to develop guidelines for designing a model of face-to-face contact and a threaded joint. This work provides insight to the modelers on how the model should be designed in the joint region.

The finite element model of MACE components and its assembled model is reported in §2 and the predications of the finite element model are compared with the modal test data. In §3 a linear dynamic model for joints is presented. The joint parameters are then tuned in so that a good correlation between the model predictions and the experimental observations is achieved. The updating procedure and its outcomes are reported in §4

2 The FE Model

MACE is an aluminum structure consist of four substructures: Case, Collar, Body and Retaining Nut. Figure (1) shows how these substructures are assembled and form the MACE structure. Two types of joints exist in the assembled structures. The Body-Collar and Body-Retaining Nut interfaces are threaded joints and the Body-Case, Case-Collar, and the Case-Body interfaces are face-to-face compression joints.

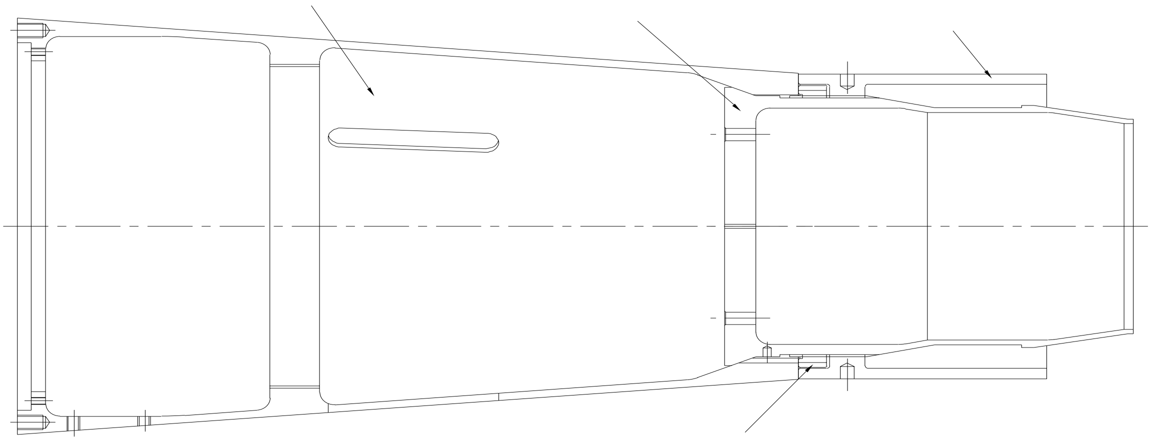

Figure 1: The MACE assembled structure

Mode No.	Case Test	Case Model	Body Test	Body Model	Collar Test	Collar Model
1	586	592	536	538	512	526
2	586	592	537	538	514	526
3	707	725	1169	1151	825	830
4	713	725	1175	1151	826	830
5	1186	1194	2005	1956	1299	1314
6	1252	1244	2013	1956	1300	1314
7	1308	1317	2056	2042	2171	2211
8	1330	1317	2065	2042	2173	2211

Table 1: The measured and predicted natural frequencies (Hz) of MACE substructures

Mode No.	Measured Modes (Hz)	Initial Model (Hz)	Updated Model (Hz)
1	603	629	618
2	604	629	618
3	806	982	807
4	807	982	807
5	1165	1232	1156
6	1169	1232	1156
7	1194	1280	1195
8	1197	1298	1195

Table 2: The measured and predicted natural frequencies of the assembled MACE structures

A finite element model for each substructure is developed using the finite element software MSC/NASTRAN. The models are formed using a combination of low order 4 noded plate elements (CQUAD4) and 8 noded solid elements (CHEXA). A comparison between the predictions of each model and its experimental observations is reported in table (1). In assembling the MACE structure the Retaining Nut is loosened after the Body and the Case are placed in the right position with respect to each other. This means that the Retaining Nut does not introduce any significant effect in the stiffness of the assembly and therefore is regarded in the model only as an added mass in the structure.

An initial model for MACE was developed by assembling the three substructures, namely the Body, the Case, and the Collar. In the initial model nodes of the substructures located on the contact interfaces were merged together. This provided much higher stiffness in the joint model than the actual value. The first ten modes of the model assembled in this way are compared with the experimentally measured modes in table (2). The experimental results were obtained by exciting the assembled structure using 2 shakers in the free-boundary-condition state. Comparing these results, one notices higher values for the analytically predicted modes. The model of each substructure individually was found to be well representative, therefore one should look for a proper procedure to tune the uncertain joint parameters.

3 The Joint Model

In the finite element model, the joints between substructures can be represented by interface elements. Different types of interface elements have been developed to model the behaviour of the joint under certain loading conditions. Two groups of interface elements are commonly used in the modelling, *zero-thickness* and *thin layer* interface elements. In the *zero-thickness* interface elements [1-3] it is assumed that the interface has a zero thickness and a constitutive law , usually consisting of constant values, for both the shear stiffness and the normal stiffness is defined. The *thin layer interface* [4-6] is based on the assumption that interface behaviour is controlled by a narrow band or zone adjacent to the interface with different properties from those of the surrounding materials. The *thin layer element* is treated as any other element of the finite element model mesh and is assigned special constitutive relations.

When an interface element is used to model a joint, an appropriate constitutive relationship must be adopted. A number of interface constitutive models have been developed. Depending on the type of analysis performed, the interface physics may be represented by quasi-linear or nonlinear models. Quasi-linear models [6-7] consider a constant value of stiffness over a range of interface displacements, until yield is reached. In nonlinear models [8-9], the interface shear stress-displacement relationship is represented by a mathematical function of higher order. The interface shear stiffness changes during shear, depending on the magnitude of the displacement and any other factors included in the model. The coupling between normal and shear deformations is often ignored and is not included in most of the constitutive formulations found in the literature.

For the joint that behaves elastically in the closed state the implemented constitutive relation can be expressed as follows:

$$\begin{aligned} \Delta\sigma &= k_n \Delta v \\ \Delta\tau_1 &= k_s \Delta u_1 \\ \Delta\tau_2 &= k_s \Delta u_1 \end{aligned} \qquad (1)$$

where $\Delta\sigma$, $\Delta\tau_1$, and $\Delta\tau_2$ are respectively the elastic part of the incremental normal and tangential stresses, Δv, Δu_1, and Δu_2 are the incremental relative normal and tangential displacements of the joint. Subscripts "1" and "2" denote the two orthogonal tangential displacement directions in the plane of the joint. Parameters k_n and k_s are penalty parameters which, respectively, simulate the no penetration condition of the joint face, and the stick or no slippage condition in the joint plane. Once the joint exceeds its elastic limit, further sliding will follow an elastic-plastic behaviour. When the interface element is in a state of sliding, a quasi-linear constitutive equation at each sliding increment can be defined as:

$$\left\{ \begin{array}{c} \Delta\sigma \\ \Delta\tau_1 \\ \Delta\tau_2 \end{array} \right\} = \left[\begin{array}{ccc} k_n(1-\mu^2 k_n/H) & -k_n k_s \beta_1 \mu/H & -k_n k_s \beta_2 \mu/H \\ & k_s(1-\beta_1^2 k_s/H) & k_s^2 \beta_1 \beta_2/H \\ Sym. & & k_s(1-\beta_2^2 k_s/H) \end{array} \right] \left\{ \begin{array}{c} \Delta v \\ \Delta u_1 \\ \Delta u_1 \end{array} \right\}$$
$$H = k_n \mu^2 + k_s, \quad \beta_1 = \frac{\tau_1}{\sqrt{\tau_1^2+\tau_2^2}}, \quad \beta_2 = \frac{\tau_2}{\sqrt{\tau_1^2+\tau_2^2}}, \quad \mu = \tan\phi, \qquad (2)$$

where ϕ is the friction angle.

In this work the joints are considered to behave (quasi-)elastically and in the closed state. This means that either there is no joint slippage and forces applied to the joints are less than the limit defined by friction and cohesion or if there is any slippage it is stable and the constitute equation remains linear.

In modelling the joints, we use the thin layer interface elements. It is easy to incorporate the interface layer into the model by allowing the elements neighboring the interface to have a different constitutive relationships from the rest. All the elements used in modelling of MACE have isotropic material properties, corresponding to aluminum, except for the interface elements. One may assign the interface elements to have an anisotropic material property to allow different normal stiffness and shear stiffnesses in the joint. In the face-to-face contact joints the normal stiffness is much higher than the shear stiffnesses. The use of an anisotropic material property for the interface layer not only accommodates different stiffness in normal and tangential directions but it also enables one to define the coupling effects, if they exist, between the normal stiffness and the shear stiffness.

The linear constitutive equation for CHEXA elements which form the interface layer is:

$$\left\{ \begin{array}{c} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{xy} \\ \sigma_{yz} \\ \sigma_{zx} \end{array} \right\} = \left[\begin{array}{cccccc} c_{11} & c_{12} & c_{13} & c_{14} & c_{15} & c_{16} \\ & c_{22} & c_{23} & c_{24} & c_{25} & c_{26} \\ & & c_{33} & c_{34} & c_{35} & c_{36} \\ & & & c_{44} & c_{45} & c_{46} \\ & & & & c_{55} & c_{56} \\ & Sym. & & & & c_{66} \end{array} \right] \left\{ \begin{array}{c} \epsilon_{xx} \\ \epsilon_{yy} \\ \epsilon_{zz} \\ \epsilon_{xy} \\ \epsilon_{yz} \\ \epsilon_{zx} \end{array} \right\} \qquad (3)$$

Assuming that at each joint the properties of interface layer remains constant from one element to the neighboring one, there are 21 parameters for each joint, i.e $c_{ij},\ i = 1, \ldots, 6,\ j = i, \ldots, 6$, to be identified. Both states defined in equations (1) and (2) are members of the family of models defined in equation (3).

Therefore by selecting the entries c_{ij} of the constitutive matrix as the parameters the joint physics in sliding or non-sliding state can be identified.

The selected parameters can be identified if they have a significant effect on the modal response of the model. Otherwise the process of identifying the parameters will be ill-conditioned and physical realizable results would not be achieved. One may introduce some relations and/or constraints into the parameter identification procedure to avoid ill-conditioning [11-12].

4 Parameter Identification

A set of modes measured in free boundary conditions are available for the MACE structure. The first 8 experimental natural frequencies are shown in table (2). These modes will be used to identify the unknown parameters of the model by tuning in the parameters so that a good agreement between the predictions of the model and the measured data is achieved.

The modes within the frequency range of interest correspond to different combinations of deformations, mostly ovalling of the cross-section, in the three sub structure with no deformation at the Body-Case interface zone. In this frequency range no bending like modes for the structure were found. The behaviour of the structure at these modes is dominated by the normal stiffness k_n at the interface layer and is insensitive to the shear stiffness k_s. To avoid any ill-conditioning in the identification process, we decided to relate k_s in the model to k_n by assuming that the interface material has an isotropic property. That is only one parameter, i.e. modulus of elasticity, at each interface layer should be identified.

The identification procedure was performed using the *Design Sensitivity Module* available in MSC/NASTRAN 2001. The modulus of elasticity of the Body-

Collar interface layer and the Case-Collar interface layer were selected as the design variables. The Body-Case interface parameter was not modified due to the fact that the modal strains at this interface were very small. The objective function for the optimization procedure was defined as:

$$min \sum_{i=1}^{n} W_i(\omega_i^e - \omega_i^a)^2 \tag{4}$$

where ω^e and ω^a are, respectively, experimentally measured and analytically determine natural frequencies, and W_i is a real positive weighting factor. The design sensitivity procedure in MSC/NASTRAN is based on an iterative linearized eigen-value sensitivity where the eigen-sensitivity is determined using the following expression:

$$(\omega_i^e)^2 - (\omega_i^a)^2 = \frac{(\phi_i^a)^T(\Delta K - (\omega_i^a)^2 \Delta M)(\phi_i^a)}{(\phi_i^a)^T M (\phi_i^a)} \tag{5}$$

We selected the first four modes of the structure (the first 2 modes each with multiplicity of 2) to be introduced into the objective functions. As there was no preference between the modes, the weighting factors were set to unity, $W_i = 1, \quad i = 1, \ldots, 4$. The rest of the measured modes were used only to determine the predictability of the updated model. A permissable range of variation for each parameter was also defined. The upper bound for the variation of the design parameters was set to 1.1 of its initial value and the lower bound was set to 0.0001 of the initial value. The selection of the bounds were based on the fact that the interface layer introduces a local softening effect and sharply reduces the normal stiffness k_n at the joint compared to the other areas of the structure. The initial value for Case-Collar parameter was set to 7.2e9, and for the Body-Collar it was set to 7.2e9.

Figure (2) shows the changes in the objective function at different iterations. The procedure shows a convergence at 10 iteration. Changes in the design variables during the optimization procedure are also shown in figure (3). It shows

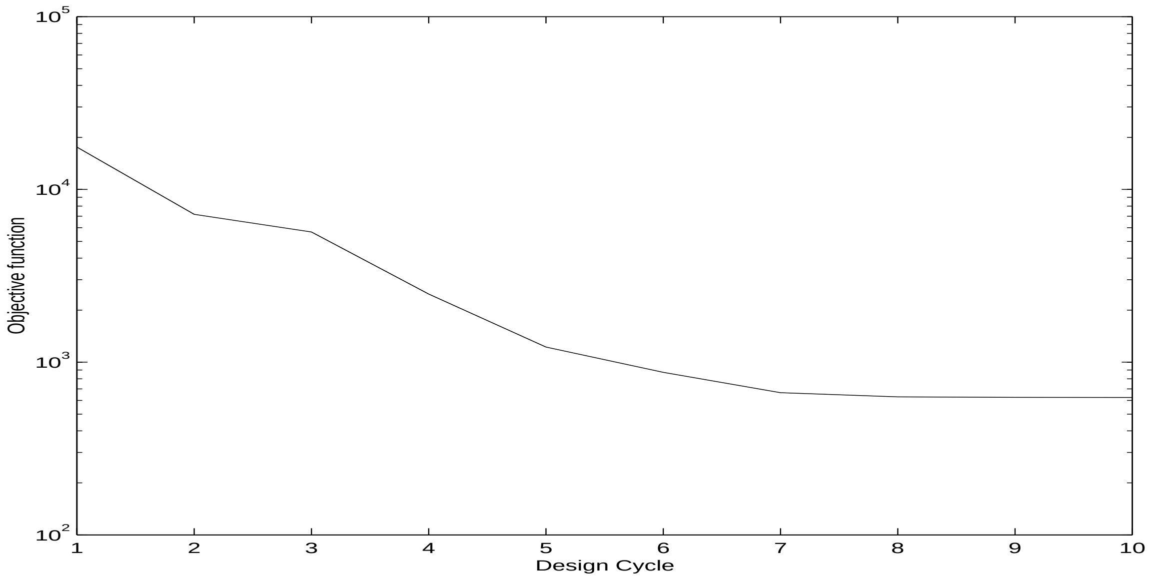

Figure 2: Changes in the objective function vs. iteration number

that the stiffness in the Body-Collar interface layer is decreased by 4 orders of magnitude from its initial value and the updating parameter for the Collar-Case interface zone is decreased by 3 orders of magnitude.

The predictions of the updated model beyond the modes used in the optimization procedure shown in table (2) are in excellent agreement with the test results. The accuracy in predicting higher modes insures that the identified interface parameters have physical merit and can be used in the model for simulations of the dynamical behaviour of the structure in the service.

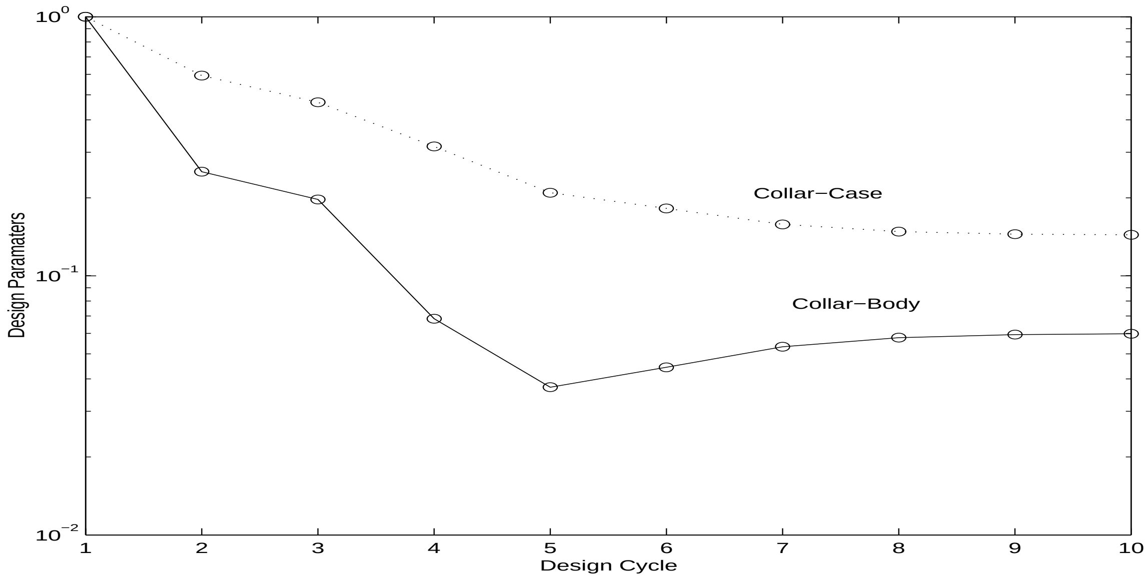

Figure 3: Changes in the interface parameters vs. iteration number

5 Conclusion

A linear dynamic model for joints using the *thin layer interface theory* is developed. The parameters of the model are determined by an inverse approach. The model can be easily incorporated into existing commercial finite element codes with the ability to define the dominant physics of the joint. The method is demonstrated by identifying the interface parameters of the AWE's MACE structure. The results show that at the interface layer the stiffness of the element is reduced significantly. This work provides insight to the modelers into how the model should be designed in the joint region.

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