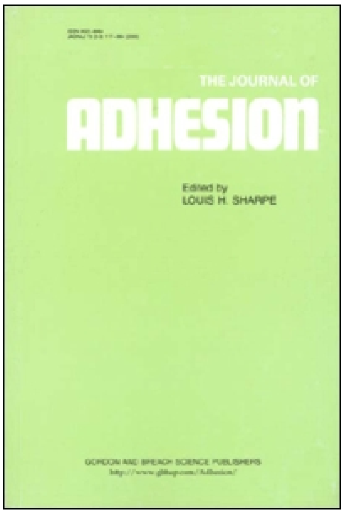

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Strength of Double Containment Joints Having Right Angle Supports

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Strength of Double Containment Joints Having Right Angle Supports

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Bonded structures are commonly made of double containment joints. The common configurations of double containment joints are right angle and T-type with corner supports. In this study, numerical analysis is used to study the joint strength for three types of double containment joints having a circular corner support, a regular right angle support, and a modified right angle support. Steel and aluminum are considered for the joint supports.

In general, it was found that the joint strength is nearly the same for joints having steel and aluminum circular cross-section supports. Further strength enhancement was obtained in the case of aluminum regular supports. Furthermore, the dynamic behavior of double containment joints with a circular cross-section was dynamically tested. The dynamic test showed that decreasing the support diameter and increasing the slot depth not only improve the static strength but also the dynamic performance.

Keywords: Adhesive bonding; Containment joint; Finite element; T-joint

1. INTRODUCTION

Adhesive bonding has been successful in replacing mechanical fasteners in some structural applications such as machine tool structures, motor cars, airplanes, and pipelines. Adhesives have also proved successful in a wide range of practical applications for bonding dissimilar materials. For example, modern gear box casings and gear unit

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housings are often made of aluminum alloys and a large number of steel studs, plugs, rings, and other components are assembled to close tolerances. Because of the varying coefficients of thermal expansion of these materials, these components become loose as soon as the units heat up during operation. The use of epoxy adhesives in such instances ensures strong sealed joints.

Adhesive bonding was introduced for machine tool construction in 1968, when a small milling machine was fabricated by bonding [1]. The reason behind the introduction of adhesive bonding for machine tool structures was its higher damping capacity.

Adhesively bonded joints have attracted the attention of many researches, where stress analyses of the deformed joints have been carried out analytically and using numerical analysis [2–13]. Since two or more different materials are used in adhesively bonded joints and the adhesive layer is thin when compared with the adherend thickness, boundary conditions make the problem complicated. The finite-element technique is an efficient method to analyze the strength of bonded joints regardless of their geometry.

Structural bonded components are developed using corner joints, in which plates with different geometries and materials are bonded using right angles and T-configurations. Chang *et al.* have used bonded structure with corner supports in the design and manufacturing of a prototype-milling machine [1]. Khalil and Davies [2] and later Darwish *et al.* [3] considered this philosophy and reported that the peak adhesive stress occurred at the junction of the cantilever plate and the support at the open end of the corner slot in the double containment cantilever joint. Apalak *et al.* [4,5] presented a new modified type of double containment joint and they were able to reduce the peak stresses in double containment corner joints. In this joint, they kept the horizontal slot depth as large as possible which resulted in slightly relieving the stress concentrations at the joint free ends and increased the overall joint stiffness, for different loading conditions, by increasing the horizontal and vertical support lengths and the vertical slot depth. They also obtained a saving of 14.9% from the corner support volume, compared with the original joint, using a shorter horizontal support length and a large horizontal slot depth.

Double containment joints are also used in the development of bonded cutting tools [6–11].

A new version of double containment joints having a circular cross-section support was proposed [13]. This proposed joint not only provides higher strength joint, and weight saving, (up to 45%) when compared with the regular double containment joint, but also provides saving, throughout its manufacturing steps (Fig. 1).

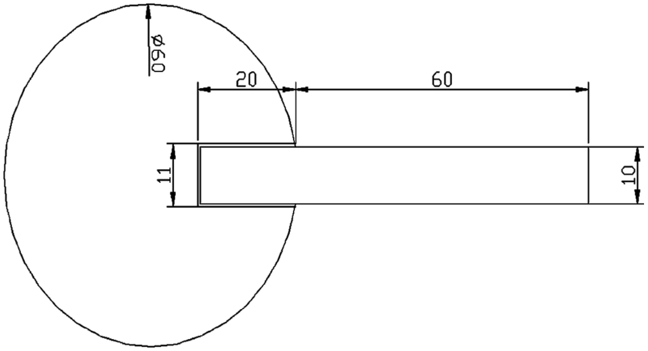


FIGURE 1 General layout of the proposed new version of double containment joints with circular cross-section corner support.

In the present work, the strength of different industrial right angle double containment joints having similar and dissimilar materials are considered. The three types of joint studied were: circular, regular and modified right angle configurations. The three dimensional (3-D) finite-element (FE) technique was used to study the joint strength for the three models. The dynamic characteristics [12] (natural frequency and damping capacity) of double containment joints with circular support were also investigated in the present work.

2. JOINT STRENGTH PREDICTION

2.1. Finite Element Model Details

The solid model and FE meshes were generated using the *GID* pre-processing program (CINME, Barcelona, Spain) [14]. The FE computation was carried out using the *Tochnog* FE program [15]. *Tochnog* is an explicit-implicit FE program that can be used in the analysis of structural, thermal, elastic, or elastic-plastic engineering problems. *Tochnog* and *GID* programs run under *Linux* (operating system). At first, the data file of the FE model was generated using the *GID* pre-processing program and completed using a text editor. Next, the *Tochnog* FE module was executed using the developed data file. Post-processing the FE results was done using the *GID* post-processing program.

The following assumptions and boundary conditions were used throughout the idealization process:

- 3D-model formulation;
- All materials are isotropic and homogeneous, *i.e.,* the properties of the materials are the same in all directions;

- The stress and strain applied on each material are in the elastic zone;
- No contact stresses are assigned to the adhesive layer.

Figure 2 shows the general layout and dimensions of the proposed double containment joint having circular cross-section, regular, and modified right angle supports. The assigned boundary and loading conditions are shown in Fig. 3. The assigned materials for the joints and material properties are shown in Table 1. The FE mesh developed for the three solid models is based on tetrahedral-type linear elements. It is worth noting that different FE-mesh capacities are investigated to ensure the solution convergence. Table 2 shows the number of nodes and elements used in mesh generation for the three FE models. Figure 4 shows the finite-element meshes developed for the three models.

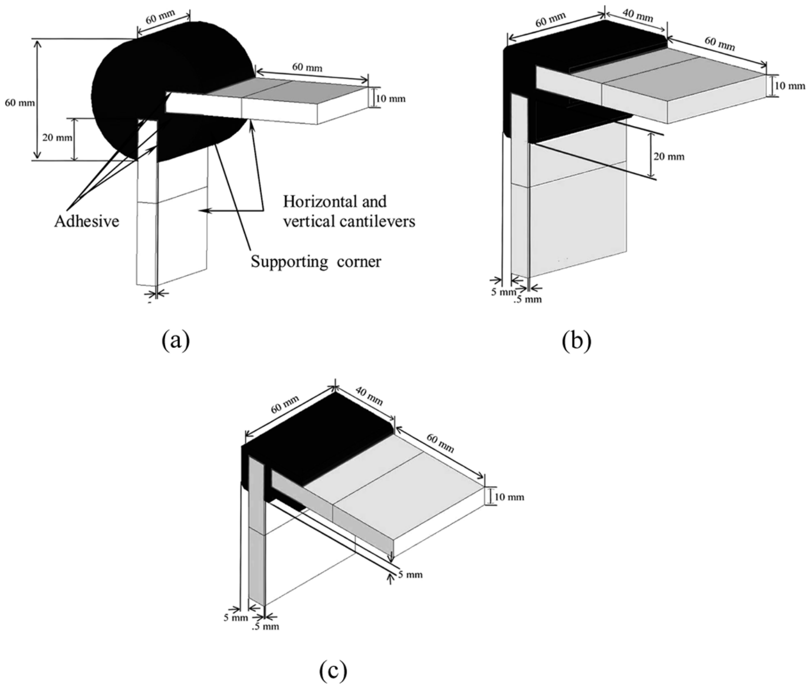


FIGURE 2 General layout and dimensions of right angle double containment joints. a) Circular cross-section right angle support, b) regular right angle support, and c) modified right angle support.

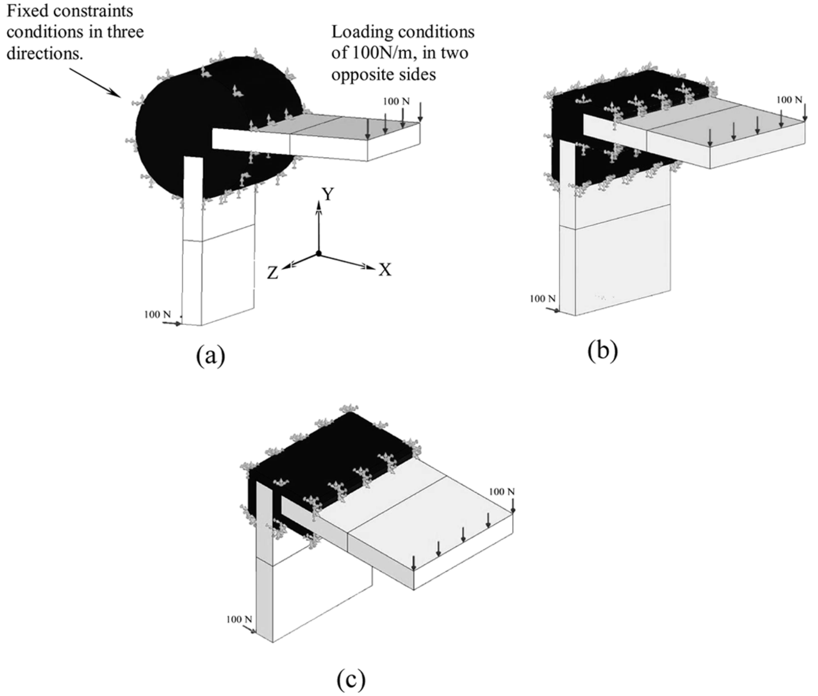


FIGURE 3 Constraints and loading conditions for the three double containment joints. a) Circular cross-section right angle support, b) regular right angle support, and c) modified right angle support.

2.2. Finite-Element Results and Discussion

The predicted Von Mises stress contours for the three FE models are shown in Fig. 5.

Since the weakest link in the joint is the adhesive layer [2–5], it was decided to report the stresses developed in the mid-layer of the adhesive between the corner adherend and the cantilever. Von Mises stress distributions are reported at three sub-layers as shown in Fig. 6

TABLE 1 Assigined Materials to the Developed Solid Model [3]

Material	Elastic modulus GPa	Poisson's ratio	Shear modulus (Gpa)
Steel	2.00E + 02	0.3	78.1
Aluminum	6.00E + 01	0.33	28.1
Adhesive	2.50E + 00	0.38	0.905

TABLE 2 Number of Nodes and Elements used in FE Mesh Generation

Model	Number of nodes	Number of elements
Circular double containment joint	78403	53610
Regular right angle double containment joint	51587	34157
Modified right angle double containment joint	54802	35029

(upper layer, back layer, and lower layers), along the mid-thickness at the adhesive.

Stresses in the bonded joint are developed due to the bonding of dissimilar materials (adhesive/adherend) and also due to joint-loading conditions (Fig. 3). Because the structure consists of two or more

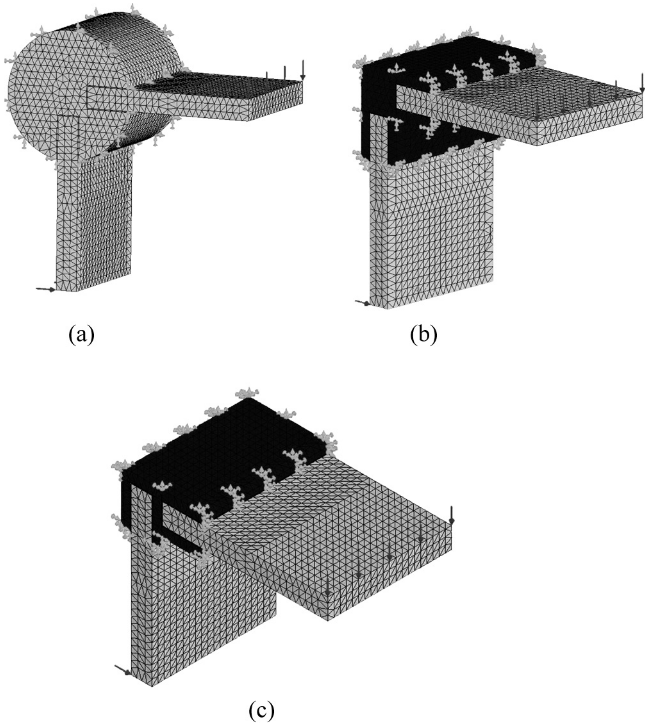
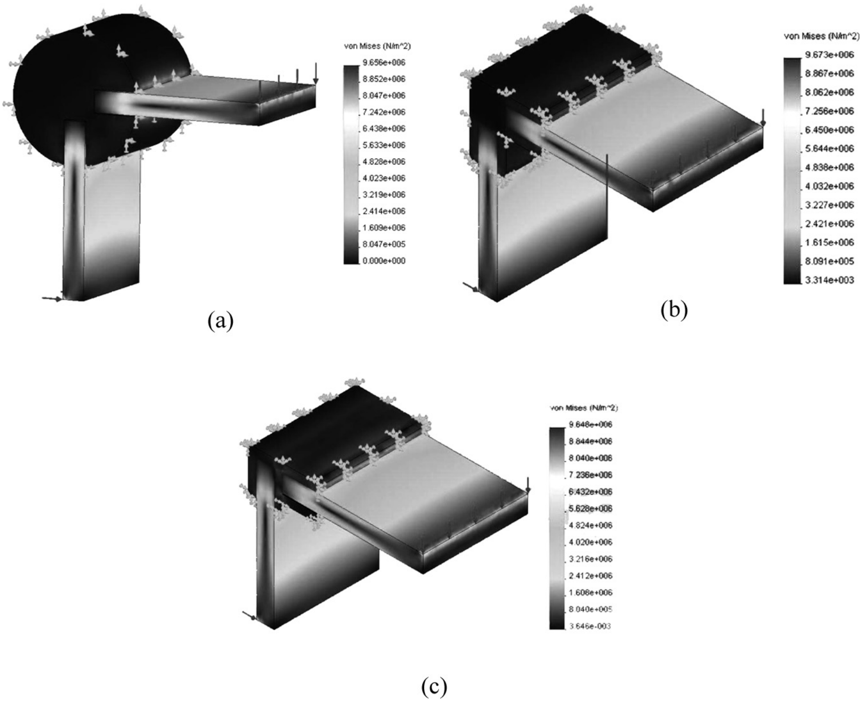

(a) (b) (c)

FIGURE 4 Finite-element mesh generation for the three double containment joints. a) Circular cross-section right angle support, b) regular right angle support, and c) modified right angle support.



(a)

(b)

(c)

FIGURE 5 Predicted Von Mises stress contours for the three double containment joints. a) Circular cross-section right angle support, b) regular right angle support, and c) modified right angle support.

materials bonded together, a state of non-uniform stress occurs. The difference in physical properties at either of the adhesive/adhered interfaces produces a varying intensity of stress. Figure 7a shows the predicted Von Mises stress distributions along the mid-layer of the adhesive upper, lower, and back bonding layers (Fig. 6). The results are shown in Fig. 7a for the horizontal and vertical cantilever sides of the steel adherend joints. The same results are shown in Fig. 7b for aluminum-steel adherend joints.

A summary of the FE results is shown in Fig. 8 for both circular cross-section, regular, and modified supports. Figure 8 shows the Von Mises stresses developed in the three FE models.

In general, the stress distribution of double containment joints gradually increases from the inner side to the outer side along the bonded direction. The maximum Von Mises stress was predicted at the open end of the corner slot as shown in Fig. 7. These results are

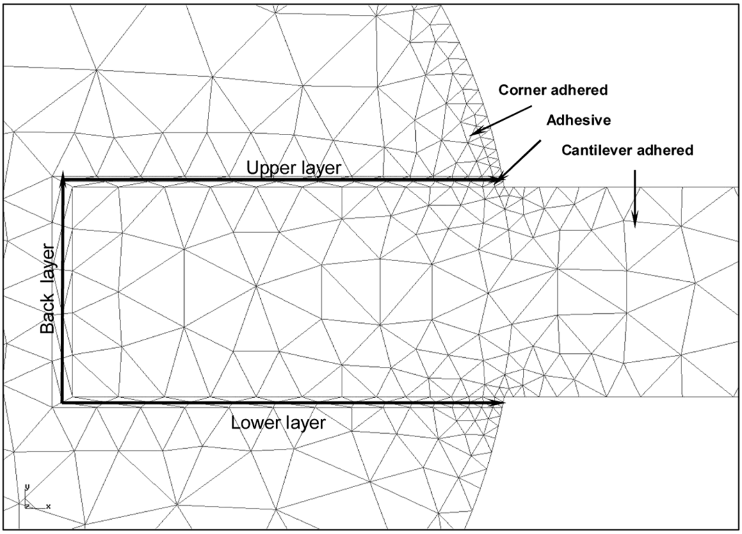


FIGURE 6 Stress monitor location along the mid-layer of the adhesive in three layers of the double containment joint; upper, back, and lower bonding layers.

reported for the three double containment joints having circular, regular, and modified supports.

From Fig. 8a, it can be seen that the peak Von Mises stress is between 6 and 10% higher for aluminum supports when compared with steel supports in the case of circular double containment joints. For the regular corner support joint, it can be seen (Fig. 8b) that the peak Von Mises stress is between 2 and 6% larger in aluminum supports than steel supports. From Fig. 8c, it can also be seen that the predicted peak Von Mises stress is between 7 and 9% larger in aluminum supports than in steel supports for modified corner double containment joints.

Furthermore, it can be observed that the peak Von Mises stress is 29% higher in modified double containment joints when compared with bo th circular and regular double containment joints.

3. EXPERIMENTAL DYNAMIC BEHAVIOR OF DOUBLE CONTAINMENT JOINT

In the present work, experimental dynamic behavior of double containment joints having circular support is tested and reported.

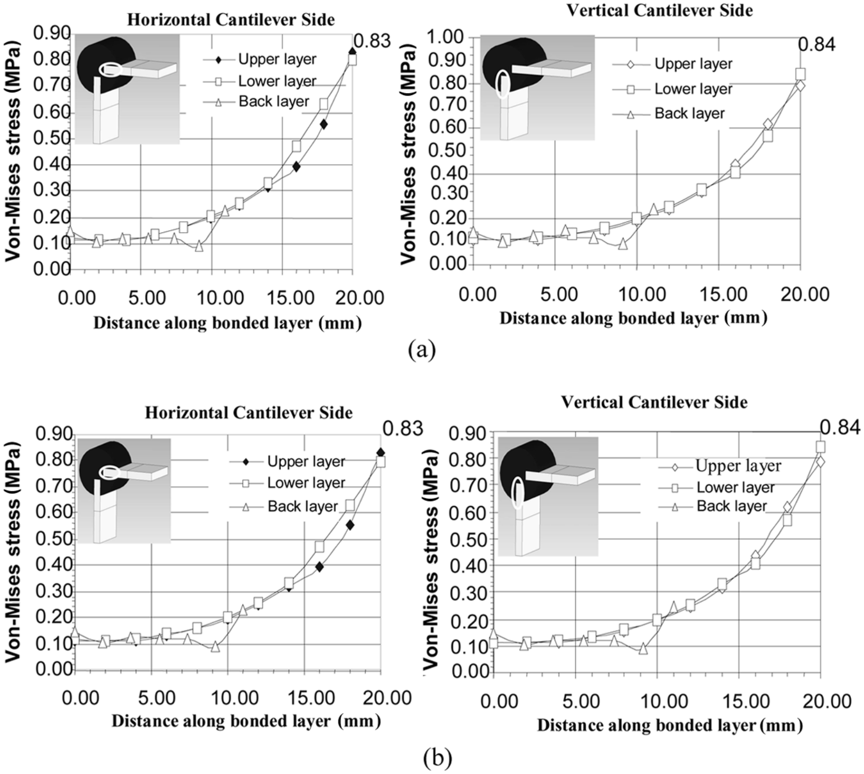


FIGURE 7 Predicted Von Mises, S_v, stress distributions along the mid-layer of the adhesive for the upper, lower, and back bonding layers for the horizontal and vertical cantilever sides. a) Steel-steel adherend joint, and b) aluminum-steel adherend.

3.1. Specimen Preparation

Three specimens were tested in the present work and described below:

Bulk Steel Specimen

Figure 9 shows the dimensions and configuration of the bulk steel specimen. The specimen was cut from a steel block ($D = 140\,\text{mm}$, $L = 30\,\text{mm}$) using a wire Electric Discharge Machine (WEDM) as shown in Fig. 9.

Bonded Steel Cantilever and Steel Support Specimen (Steel-Steel Specimen)

The specimen has the same configuration and dimensions as the bulk steel specimen. The support of the specimen was machined on

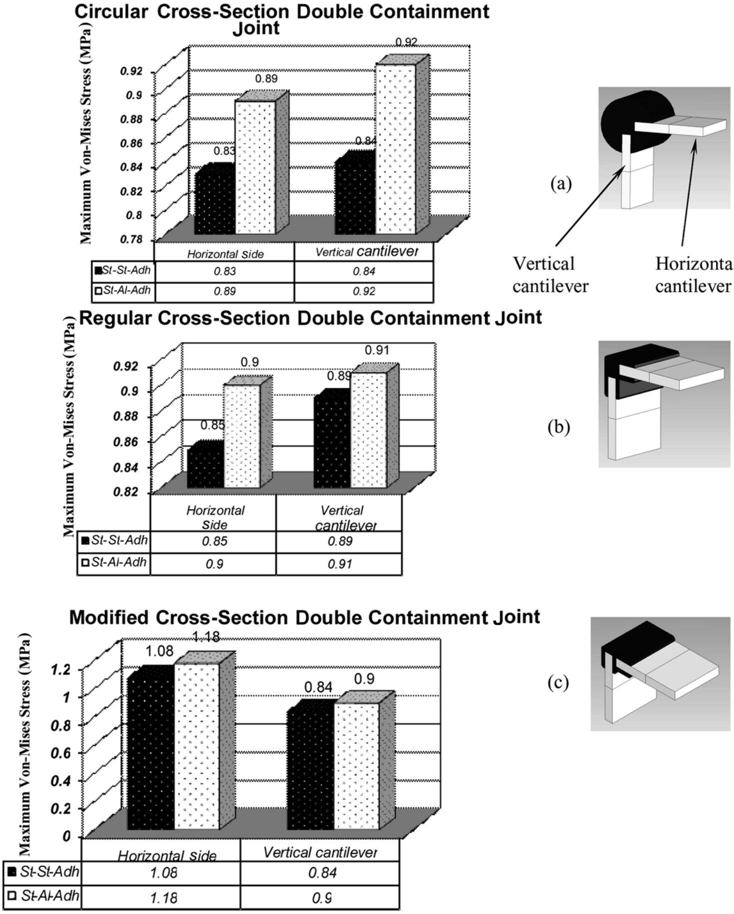


FIGURE 8 Peak Von Mises stresses developed in double containment joints with steel/steel and steel/aluminum corner supports. a) Circular supports, b) regular supports, and c) modified supports.

an engine lathe, then slot milled on a vertical milling machine. A general layout of the specimen is shown in Fig. 10.

Bonded Steel Cantilever and Aluminum Support Specimen (Steel-Aluminum Specimen)

In this specimen, the steel support of the joint is replaced by an aluminum support. This helped to reduce the weight and increase the natural frequency of the specimen.

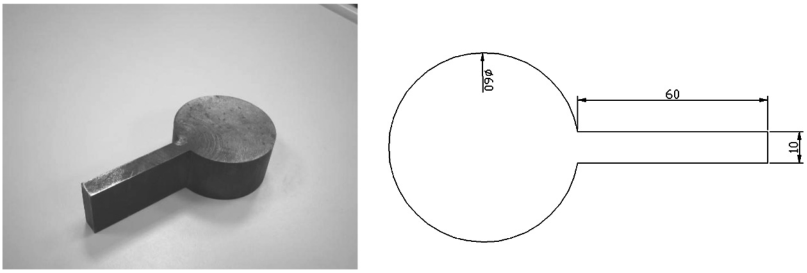


FIGURE 9 Bulk specimen processed on wire EDM machine (dim in mm).

Clean, dry, firm surfaces are necessary for reliable adhesive bonding production and problems may be encountered due to pre-treatment of the adherend. Two techniques of surface preparation have been used for cleaning the components of the specimens. The first was used for cleaning steel parts and involved using carbon tetrachloride (in a cleaning plant, for safety reasons). The second technique of etching with sulfuric acid (aqueous 5%) was used for preparing the aluminum components of the specimen. Since the test was running at room temperature, it was decided to use the room temperature-cured two-part epoxy resin adhesive Araldite® 2004 (Ciba-Gegy, Cheshite, UK). The mixing ratio of resin to hardener was 100:40 by weight. Before applying the adhesive, a vacuum pump was used to remove air bubbles from the adhesive mixture. In order to control the bond line thickness the circular joint was fixed on the table of a vertical

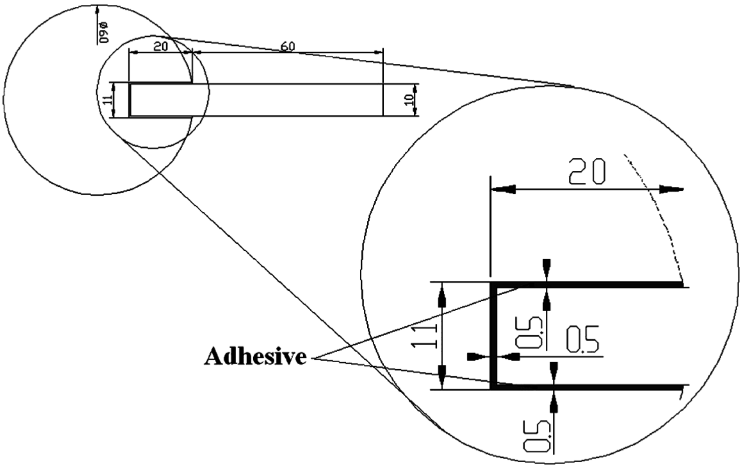


FIGURE 10 Bonded specimen geometry, adhesive thickness (dim in mm).

milling machine while the cantilever was fixed to the spindle. Horizontal and lateral movement of the table was used to insure the uniformity of the bond line thickness.

3.2. Experimental Procedure

The experimental setup used throughout the present work consists of a 4332 B&K (Stockholm, Sweden) accelerometer, a 2635 B&K amplifier, A/D converter, and Snap-Master® software for Windows [16]. Snap-Master (HEM Corporation, Southfield, MI, USA) is a PC-based data acquisition, analysis, control, and display software which performs a Fourier analysis on both the original and the filtered signals. Snap-Master combines advanced data acquisition and storage capabilities with time and frequency domain analysis and near real-time plotting. Figure 11 shows a block diagram for the experimental set-up used.

In order to assess the advantages of double containment joints having circular support over the bulk steel joint, a preliminary study was conducted with three sets of specimens, one of which was made of bulk steel while the others were made of steel-steel and steel-aluminum. The specimens were laid on a foam material and stimulated with a hand held hammer from the other end. Throughout the test, it was decided to hit the specimen in the horizontal direction; this was believed to stimulate the bonded region rather than the whole specimen. The output signal was detected by the accelerometer and fed the Snap-Master program through the A/D converter. Table 3 gives the pilot study results. From the table it can be seen that the natural frequency increased by 2 and 53% for steel-steel and steel-aluminum joints when compared with the bulk steel joint, respectively. Since the steel-aluminum joints given both higher natural frequency and damping capacity, it was selected for the next stage.

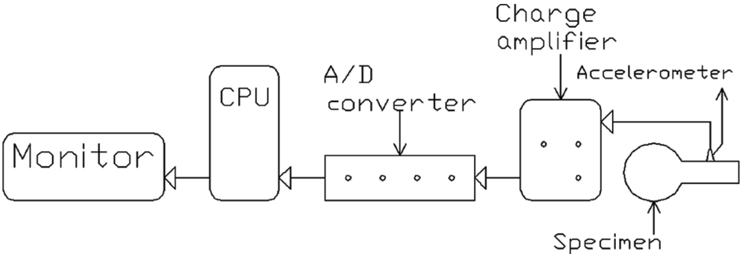


FIGURE 11 Block diagram of the experimental setup for dynamic measurements.

TABLE 3 Pilot Study Dynamic Results

Specimens	Natural frequency (Hz)	Damping coefficient
Bulk solid steel	1900	0.007391
Bonded steel-steel	1940	0.00630
Bonded steel-aluminum	2900	0.006273

3.3. Results

The factorial design was used to study the joint parameters (support diameter, slot depth, and cantilever length) between two levels, (Table 4). This yielded eight combination models (Table 5). For each model, the vibration natural frequency and damping were measured experimentally.

The specimens were all excited and the results were obtained using the Snap–Master frequency analyzer software and the results are given in Table 6.

From Table 6, it can be observed that:

- When the joint diameter was changed while the two other variables were kept unchanged, smaller diameters give higher natural frequency and damping capacity.

TABLE 4 Parameters Levels of Design of Experiment

Factor	High level (+)	Low level (−)
Support diameter	60 mm	50 mm
Slot depth	20 mm	10 mm
Cantilever length	80 mm	40 mm

TABLE 5 Model of Possible Combinations

Model number	Joint diameter	Slot depth	Cantilever length
1	−	−	−
2	+	−	−
3	−	+	−
4	+	+	−
5	−	−	+
6	+	−	+
7	−	+	+
8	+	+	+

TABLE 6 Experimental Results

Model number	Natural frequency (Hz)	Damping coefficient
1	2000	0.002388
2	1940	0.001929
3	1980	0.003442
4	1930	0.002591
5	2740	0.002479
6	2170	0.005604
7	1880	0.003312
8	2920	0.006273

- When the slot depth was changed while the two other variables were kept unchanged, larger slot depths give higher damping capacity without affecting the natural frequency considerably.

4. CONCLUSION

- Although the regular double containment joint develops slightly higher Von Mises stresses compared with the circular support, it is recommended to be used due to its lower manufacturing cost (circular cross-sections for manufacturing corner support are available on the market).
- Although the predicted Von Mises stress is 10% higher with aluminum supports compared with steel supports, it is recommended to use aluminum metal for the joint support to decrease the general structure weight.
- Bonded steel-aluminum specimens show higher natural frequency than bulk steel and bonded steel-steel specimens.
- Decreasing the support diameter gives higher natural frequency and damping capacity.
- Increasing the cantilever length, while keeping the joint diameter and slot depth unchanged, resulted in increasing both the natural frequency and the damping capacity.
- Increasing the slot depth has a limited effect on the natural frequency while it increases damping capacity.

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