Sandia National Laboratories

WHITE PAPER

On the Development of Methodologies for Constructing Predictive Models of Structures with Joints and Interfaces

from the
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SUMMARY

This paper contains a discussion of the state of the art in joint mechanics as discussed in a Sandia workshop held on April 25th and 26th of the year 2000 and a statement of the need for developing methodologies for constructing predictive models of structures with joints and interfaces. It was the view of an internationally renowned group of practitioners, researchers, and program managers (Sandia, NSF, AFOSR, ONR) attending this workshop that the topic of joint mechanics is of fundamental importance for both weapons applications and other applications involving complex mechanical/structural systems because

- joint mechanics is an important contributor to the survivability of weapon systems and other complex structural systems,
- truly predictive dynamic modeling is now hobbled by an inability to account for joint and interface mechanics.

Several very different and important perspectives of future work were agreed upon in this workshop. They were

- ✓ controlled experiments to understand the basic physics of joints and interfaces need to be constructed,
- ✓ high fidelity, physics based models constructed only from basic mechanics and the intrinsic properties of materials and associated mechanics should be developed taking advantage of advanced computational capabilities,
- ✓ inverse tools to interpret experimental results in terms of interface mechanisms need to be derived,
- ✓ model reduction methods for joints and interface mechanisms need to be developed,
- ✓ benchmark problems to compare solution methodologies need to be defined,
- ✓ controlled experiments that can be used to model the effects of localized joints on the structural dynamics of systems with specific boundary and forcing conditions need to be performed, and
- ✓ uncertainty and variability effects must be accounted for in both experimental, and modeling/simulation techniques used to analyze and represent joints and interfaces.

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WHAT IS THE PROBLEM?

> … weapon systems are comprised of several thousand parts…

> … the proper representation of joints and interfaces is important to the survivability and functionality of many complex structural systems.

In weapon programs, the need for predictive models of structures with jointed interfaces is imperative since many weapon systems are comprised of several thousand parts whose responses are determined by joint and interface mechanics. With the present moratorium on underground and full-scale nuclear testing, and the current desire to reduce defense spending while maintaining safety and reliability, it is simply not possible to certify many systems or components without the use of advanced modeling and simulation techniques. Since the damping and stiffness of many structures is dominated by the response of joints and/or interfaces (Figure 1), the proper representation of these joints and interfaces is important to the demonstration of survivability and functionality of many complex structural systems. Nevertheless, most commercial and in-house modeling tools have extremely limited capabilities to model joints and interfaces. Instead, the effects of joints and interfaces are typically accounted for by tuning models to match the characteristics of experimental data. With the loss of full-scale testing, this can no longer be done.

In the future, models must be *physics based*. That is, these models must be constructed only from the separable, intrinsic properties of the materials that comprise a system. To do this, these properties must be integrated into a series of increasing length scale models to produce a final system dynamic representation.

Figure 1: The components, joints, and interfaces in typical weapon systems

THE STATE OF THE ART

In the present environment of limited testing, (model tuning or parameter estimation) is often no longer sufficient.

At present, three popular modeling methodologies exist for representing the dynamics of structures with joints and interfaces.

- The methodology of model tuning, or parameter estimation of global system parameters is commonly used. This methodology employs input-output data from hardware tests to update a model of the full-scale system, subsystem or component. Of course, this methodology requires testing of as-built hardware, and therefore, does not allow for the prediction of system or component level responses in the event of a design modification without the reconstruction and retesting of hardware. For many applications, this defeats the purpose of the simulation. Thus, in the present environment of limited testing, this methodology is often no longer sufficient.
- A combined experimental/analytical classification methodology is sometimes used. This methodology involves discovery experiments of the fundamental physical behavior specific to a restricted class of joints. These fundamental physics are then used to describe any joint within the class. Although this is often the only practical approach that can be taken, the generality of this methodology is limited. If a joint is modified in such a way that it no longer belongs to the same class, its ability to be modeled, will be constrained.
- In principle, systems could be modeled from the most basic building blocks that make sense for the application. This is often referred to as a *physics based* methodology. Micro-scale modeling or computational materials modeling could be used to predict constitutive relationship that could subsequently be used in meso level or continuum level models. No full-scale or classification testing would be required to use this methodology. For joints or interfaces, this would require modeling small-scale interactions at the asperity level before integrating these models into models of interfaces or joints. Of course, this methodology would be computationally and/or analytically complex.

In the future, models of weapon systems and other complex structural systems should be developed from a *physics based* methodology

In the future, models of weapon systems should be developed from a *physics based* methodology. This will require the use of advanced computing capabilities and high resolution, high fidelity models including nonlinear effects, dissipation effects, micro-scale effects, and possibly non-continuum behavior effects; however, to do this, some critical limitations in the state of the art must be overcome. These include the development of improved methods of nonlinear model reduction and inverse analysis, and an improved understanding of the physics of joints and interfaces.

… sufficient, non-linear, reduced order models of joints and interfaces simply do not exist.

In addition to high fidelity, full physics based models, reduced order models of joints and interfaces must also be produced. Due to the length scales at which jointed interfaces must be modeled, the size of any system model containing interface dynamics and possessing only *physical degrees of freedom* (DOF) will be computationally excessive. This is true for even the largest computers predicted for the next ten years (>100's of billions of DOF). To overcome this problem, model reduction methods that reduce the number of *physical degrees of freedom* in the system by *using a smaller number of generalized degrees of freedom* need to be developed. *Physical degrees of freedom* are degrees of freedom with physical meaning (such as the displacement of a portion of the structure in a given direction); whereas, *generalized degrees of freedom* are those not directly corresponding to physical responses (e.g. modal coefficients). At present, sufficient, non-linear, reduced order models of joints and interfaces simply do not exist, thus, hindering predictive modeling at the system level.

… sufficient constitutive relationships for the intrinsic character of interfaces do not exist.

Also, the intrinsic behavior of joint interfaces is still poorly understood. Even if reduced order models of joints existed, the validity of these models would still be called into question since sufficient constitutive relationships for the intrinsic behavior of the interfaces represented within these models do not exist. In most cases, a simple, but inexact, Coulomb friction approximation is made. Models using this approximation tend to be repeatable and deterministic. However, real joints and interfaces tend to manifest highly non-repeatable, non-deterministic behavior.

WHAT NEEDS TO BE DONE?

The physics of interfaces needs to be understood

A better understanding of the physics of joints needs to be developed.

A better understanding of the physics of joints needs to be developed. At present, Coulomb friction is the most common friction model used to represent losses in dry joints. This, of course, is a tremendous generalization. Coulomb friction is a simple, but often inaccurate, approximation of a complex series of interactions between asperities at connecting interfaces. These asperities can undergo elastic/plastic interactions, chemical and electrostatic reactions, and intermolecular and atomic interactions. Coulomb friction is also time invariant; however, as surfaces rub, the structure of these asperities change, and therefore, so does the response of the interface. This behavior is not captured in joint models based on Coulomb friction.

Even though interface interactions can be extremely complex, a high level of fidelity may not need to be used to represent friction in joints. Since joint friction is highly variable, friction models with a nominal representation and uncertainty bounds might be used.

Inverse tools to interpret experimental results need to be derived

Better methods of measuring the distribution of stress at interfaces need to be developed.

To better understand the physics at interfaces, better experimental observations must be made; however, experimentally observing interface interactions is a very difficult exercise. For example, Figure 2 shows the complexity of even a simple bolted joint. Excluding the interfaces in the nut of the bolt, over eight interfaces exist in this joint. Depending on the level of excitation, all or a portion of these interfaces can undergo micro-slip, slap, or macro-slip.

To validate a numerical model of this joint, the shear stresses at the interfaces must be observed experimentally; however, there is now no non-intrusive measurement technique available to perform this task. Only the gross or surface motion of the joint can be evaluated. Therefore, better methods of measuring the distribution of stress at interfaces need to be developed.

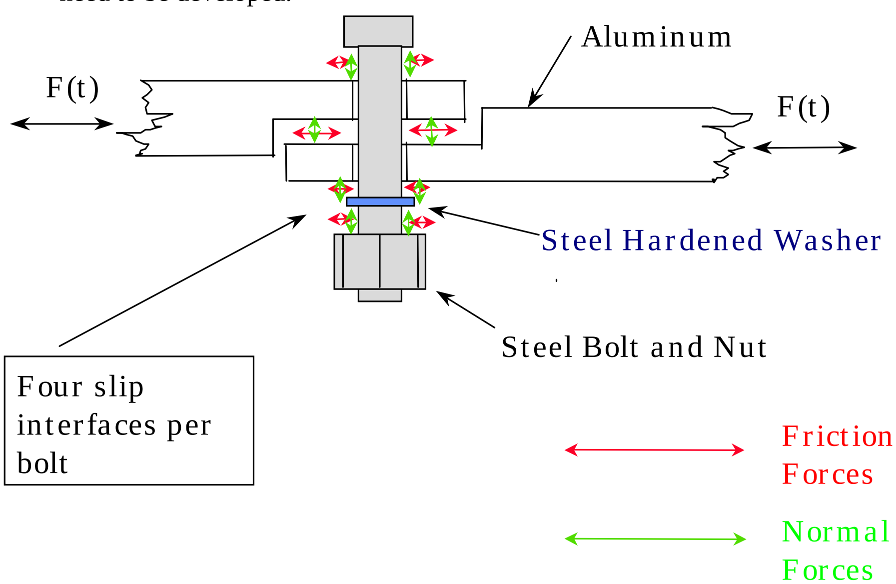


Figure 2: The interfaces in a simple bolted lap joint

Due to the computational limitations of even the largest computer, the number of degrees of freedom used to model a joint in full system models must be relatively small.

Reduced order models of interfaces need to be developed

With a better understanding of the physics of joints, attention can be turned to the development of new methodologies for modeling. These methodologies should result in models of joints that can be integrated into full-scale continuum (e.g. finite element) models of weapon systems. High order, full physics models are needed to predict the local response of individual joints; however, due to the computational limitations of even the largest computer, the number of degrees of freedom used to represent joint responses in a full system model would be prohibitive. Therefore, sufficient model reduction methods must be applied or developed for full system analyses.

Benchmark Experiments need to be developed

To compare modeling methodologies, it was proposed at the workshop to develop a number of benchmark test bed structures and a number of test beds were agreed upon. These test beds ranged in complexity from simple to very complicated. It is important to realize that scalability is a difficult but very important issue for any test bed. This includes dimensional scalability as well as frequency scalability. Input was received the day of the workshop regarding the design of these test beds, and a small subset of researches met after the workshop to decide on the final design of the level 1 and 2 test beds.

Test bed, Level 1

This test bed has a simple geometry with a single mode of vibration below 200Hz. It contains a single joint and is easy to test. The plans for this bed structure are shown below. Two separate test fixtures were constructed for this test bed. One test structure was machined out of a solid piece of material. This test structure contains a joint that has no interfaces. Therefore, losses are mainly due to material damping. The second test structure consists of the same geometry but with a true joint. This joint is constructed from two plates butted together and sandwiched by two smaller plates. These test structures were constructed and tested at Sandia.

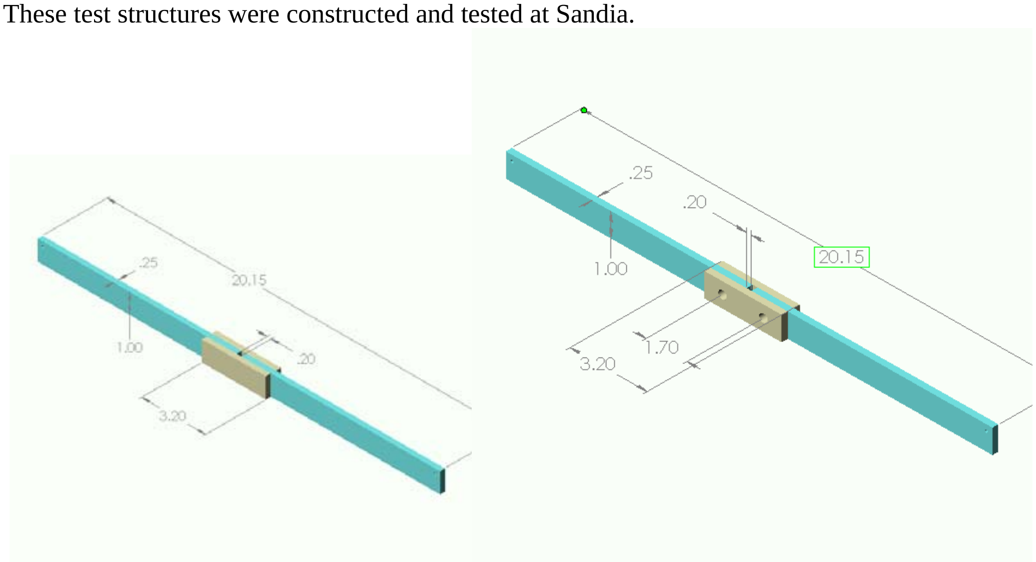
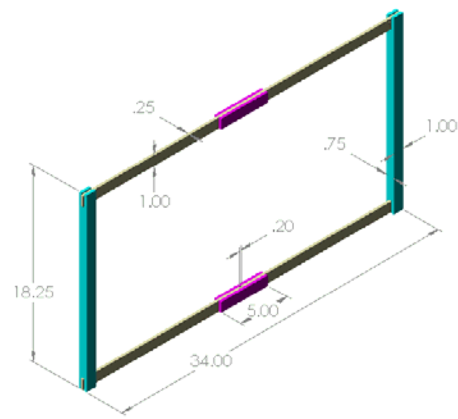


Figure 3: Level 1 Test bed structure under free-free boundary conditions

Test bed, Level 2

The level 2 test bed consists of plates of steel of various thicknesses comprising a single open bay. In the lower central section of the bay are four holes used to attach two small plates.



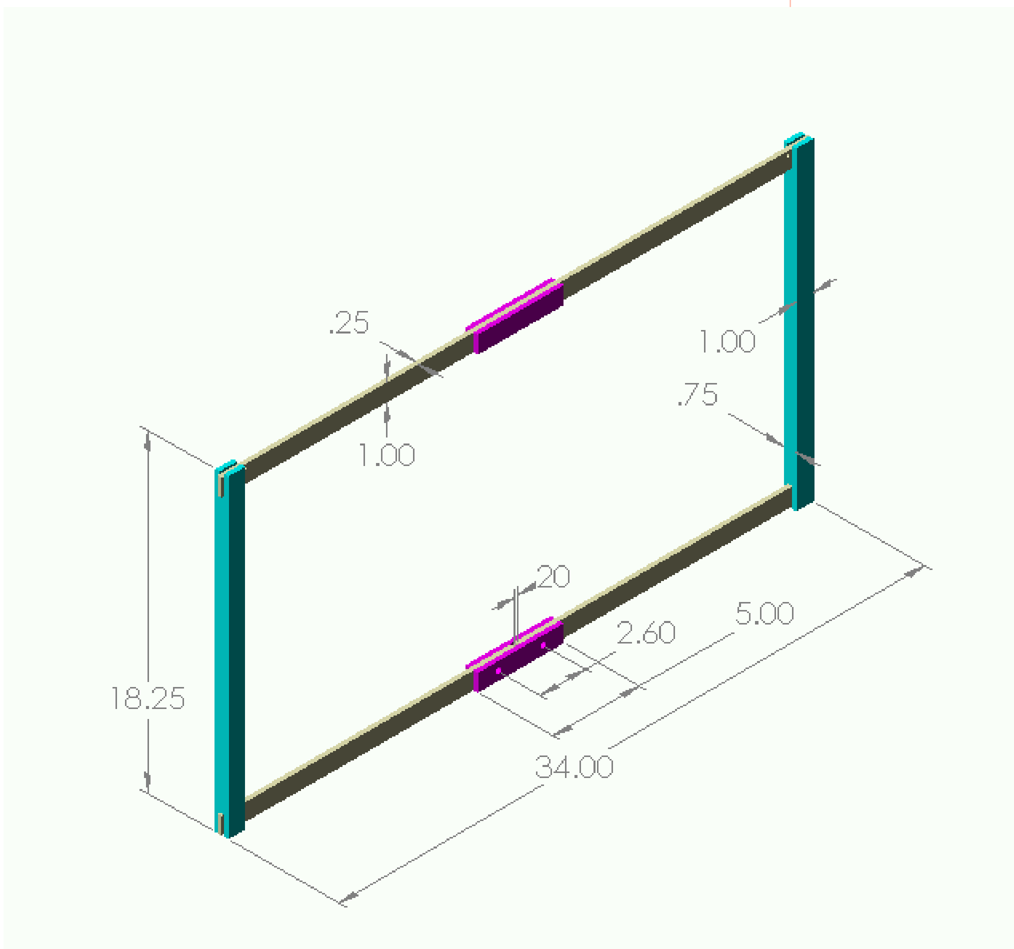


Figure 4: Level 2 Test bed structure under free-free boundary conditions

Test bed, Level 3

The Level 3 Test Bed, like the Level 2 Test Bed will still be simple to test; however it will include more realistic detail and will be reconfigurable. Figure 5 shows *an* initial design for the level 3 structure. This structure consists of a group of bent bars that are connected with a set of bolted joints. The structure can be disassembled and reassembled to take on a number of different configurations or can be bolted to a rigid support.

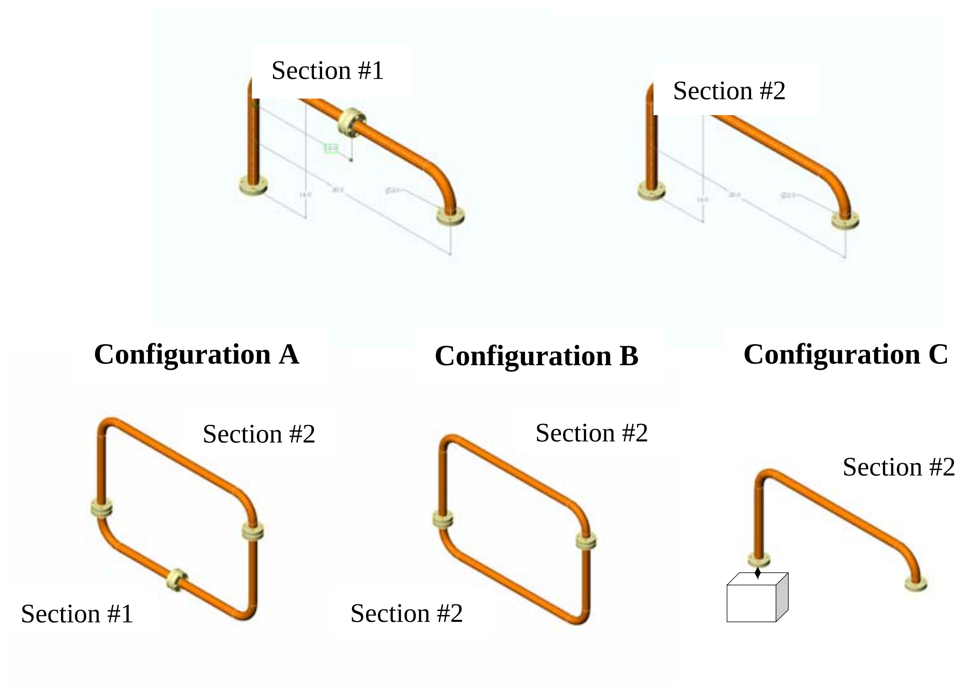


Figure 5: Level 3 Test Bed

CONCLUSIONS

Better methods for modeling joints and interfaces in weapon systems and other complex structural systems need to be developed. This need stems from the fact that joint mechanics are an important contributor to the survivability and functionality of many systems and that past methods of analysis are no longer applicable in a world with limited full-scale testing. To improve the state of the art in the modeling of structures with joints and interfaces, the participants of the Sandia workshop on the modeling and simulation of structures with jointed interfaces suggest the following areas of development.

- ✓ Controlled experiments to understand the basic physics of joints and interfaces need to be constructed.
- ✓ High fidelity, physics based models constructed only from the separable, intrinsic properties of the materials and associated mechanics should be developed taking advantage of advanced computation capabilities.
- ✓ Inverse tools to interpret experimental results in terms of interface mechanisms need to be derived.
- ✓ Model reduction methods for joints and interface mechanisms need to be developed.
- ✓ Benchmark problems to compare solution methodologies need to be defined.
- ✓ Controlled experiments to model the effects of localized joints on structural dynamics under specific boundary conditions and forcing functions need to be performed; and
- ✓ Uncertainty and variability effects must be accounted for in experimental and modeling and simulation techniques applied to joints and interfaces.

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PARTIAL SET OF CONDENSED NOTES FROM WORKSHOP ON THE MODELING AND SIMULATION OF STRUCTURES WITH JOINTED INTERFACES

Overview of Workshop
Presented by David Martinez and Jeffrey L. Dohner

- We need to experimentally discover the physical behavior and mechanics of joints and interfaces.
- We need to develop high fidelity, full physics based models of individual joints and interfaces.
- We need to focus our efforts on joint models that can be easily integrated into finite element models.
- We need to allow for micro-scale studies in the development of joint models.
- We need to understand (determine) how uncertainty should be incorporated into joint and full-scale models.
- We need to develop reduced order models that capture the important physical effects of joints and interfaces.
- We need to develop hardware test beds that can be used by the community to understand physics, guide modeling efforts, and compare modeling techniques.
- We need at least four levels of test beds

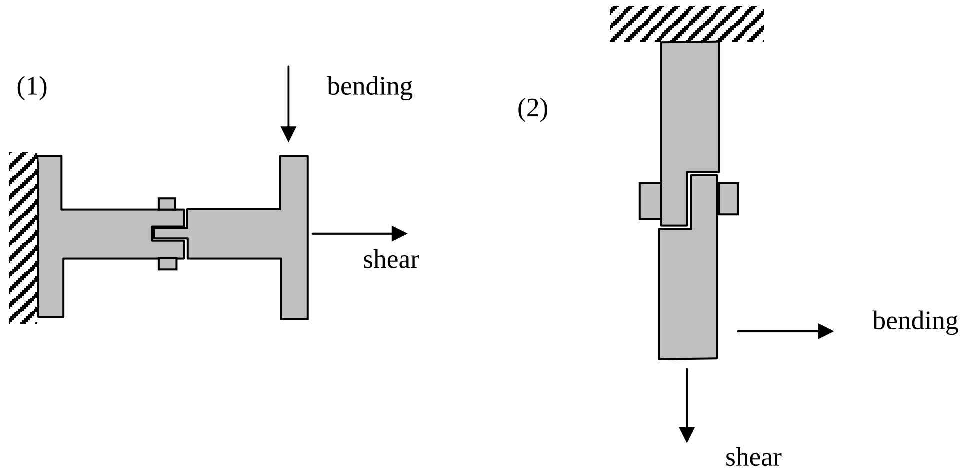
Level 0 test bed - This test bed will be a structure for us to learn the basic mechanics of joints. It should be as simple as possible.
Level 1 test bed - This test bed will be a well thought out controlled structure with more detail and complexity of behavior than that of the level 0 test bed.
Level 2 test bed - This test bed should be a realistic application.
Level 3 test bed - This test bed should be a large-scale test bed of a complex structural system.

Group I recommendations
Presented by K.C. Park and Todd Simmermacher

It was recommended that the results of the workshop be documented by:
- constructing a white paper that contains a summary of the workshop,
- tasking the organizers and group leaders to select participants to draft this white paper,
- circulating this white paper to participants for comments,
- making this white paper available to the public (including funding agencies).

Recommendations for the improvement of the level 1 test bed were also made.

- This test bed should be very scalable.
  1. dimensional scalability
  2. frequency scalability
  3. different modes of deformation
- It was suggested that this test bed be constructed such that different excitation directions and different sources induce stretching, sheer and bending deformation; (e.g. see below).
- Perform isolated joint tests and then integrated joint/structure tests.
- The objective of this testing should be to isolate the joint properties needed to predict the response of more complex structures



Group II recommendations
Presented by Alexander F. Vakakis, Steve Wojtkievicz, and Dan Inman

It was recommended that we document and disseminate the results of the workshop:

- Create a white paper and distributing that paper to all of the participating members,
- Summarize the result on the workshop on the SD2000 web page,
- organize sessions at upcoming conferences to enhance research in the area -- in particular, SAVIAC, IMAC, and ASME DETC.
- Meet again some time during next year's ASME DETC conference.

Recommendations for the improvement of the level 0 test bed design were also made.

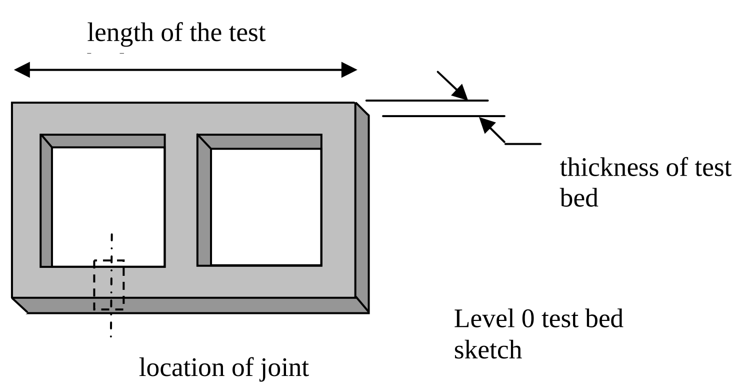
- The level 0 test bed is too small to be effectively tested. Therefore, it was recommended that the size of the test bed be increased. It was recommended that one of two modifications to the level 0 test bed should be made. These modifications would make the test bed large enough such that many difficulties encountered with testing the very lightweight preliminary test bed would be eliminated. As a result of these modifications, the size of the test bed would increase, but the location of the natural frequencies would not change significantly. The natural frequencies of the test bed will approximately obey the relationship

$$f_n \propto t / l^2$$

where f_n is the nth natural frequency of the test bed, t is its thickness, and l is its length.

Modifications to the dimensions of the test bed were made and many of these changes were incorporated into the final design presented in the body of this paper.

- It was also recommended that the location of the joint be moved to a location where the joint would be better exercised by the first mode.

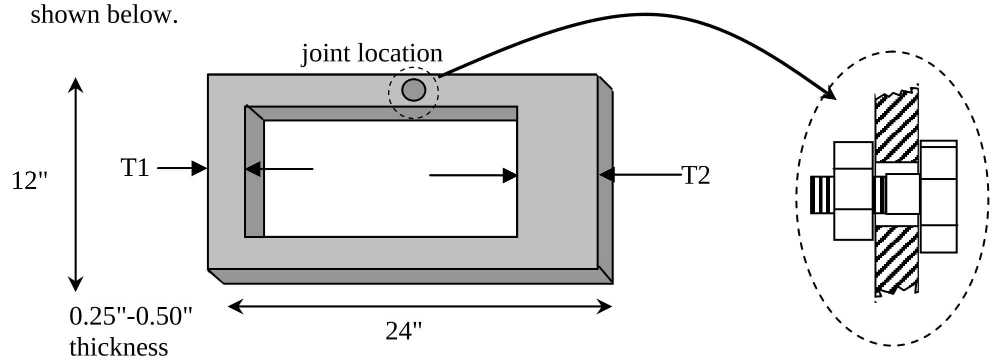


- It was recommended that a number of characteristics from this structure be measured and disseminated. In particular, the force displacement response of the joint and the energy dissipation per cycle verses force amplitude at different frequencies were of interest.
- From information disseminated, modelers could attempt to model this test bed and predict its response.

Group III recommendations
Presented by Larry Bergman and Danny L. Gregory

Group III recommended reducing the complexity of the level 0 test bed by changing its geometry and recommended increasing its mass for the purpose of minimizing difficulties with testing.

- It was recommend to not use a two bay truss structure but to use a one bay truss structure as shown below.



- The structure should have its first mode below 100Hz.
- This structure should be simple to model.
- The location of the joint should be such that it is well exercised by the first mode.
- It was recommended that the joint not be complex. A simple hole with a bolt, a nut and two washers was recommended.
- The structure should be modeled in a number of different configurations.
  - linear model with joint
  - linear model with mass loading due to the presence of a joint
  - non-linear model with a joint containing micro-slip

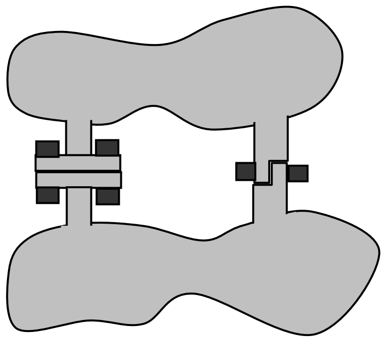
Group IV recommendations
Presented by David Ewins, Dave Smallwood, and Ken Alvin

Group IV presented recommendations for the improvement of the level 1 test bed. They believed that a very well thought-out test structure was needed.

Criteria/Specifications
- Easy to test, easy to analyse
- Allow for shaker excitation
- Design a portable structure with well-separated modes
- Excitable into non-linear range
- Design in a strong point for high-level impulsive loads
- One or two controlled joints
- Joints should be exercised in fundamental modes, and have realistic responses
- Modular with multi-configuration, multi-material possibilities
- Optional rigid base for fixed joint characteristics
- Use hardware with no joint as a reference case
- Employ a real designer to detail the design

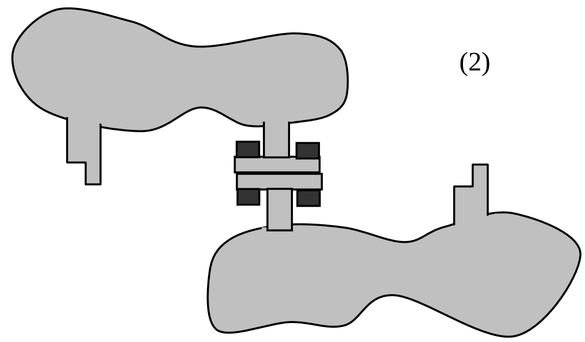
It was suggested that the level 1 test bed be one that could be reconfigured to exercise its joints a number of different ways.

(1)



This type of structure could be easily reconfigured to determine the suitability of the joint model in different systems. For example, the below structures contain only two substructures and two joints.

(2)



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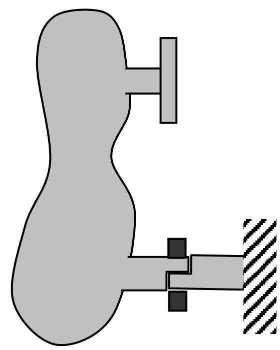

Test Objectives

- Measure FRFs using harmonic excitation as well as others
- Use controlled levels of input, over realistic frequencies of interest
- Include multiple frequency components to enable the study of NL effects
- Extraction of modal parameters
- Measure transient response to impulse loads

Other Options

- Static stiffness measurements
- Localise measurements across joint on rigid base
- Obtain hysteresis measurements

ACTION ITEMS FROM WORKSHOP – CONSENSUS OF ALL SUBGROUPS

- Develop a web site with summary of workshop
- Link workshop results to the SD2000 web site
- Compile proceedings of workshop and include in website
- Produce a white paper documenting the results
- Identify a number of research groups (five to six) that would commit to following the outlined research program: The initial phase of that program would be to test and characterize the joint dynamics of the level 0 testbed. We proposed that the results from the participating groups be presented and discussed in a Forum to be held at ASME DETC, September 2001.