

THE DAMPING CHARACTERISTICS OF BOLTED AND WELDED JOINTS

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Introduction

Damping is a dissipation mechanism in which vibration energy is transformed into heat or some other energy form which is lost from the vibrating system.¹ Engineering structures require a certain minimum amount of damping for vibration control, particularly if the structure is excited at its natural frequency. The vibration response must be limited to avoid failures due to fatigue, yielding, loss of clearance, etc.

This tutorial is concerned mainly with the damping in structures composed of connected beams, such as buildings and towers.

Joint Damping Mechanisms

The primary damping mechanism at joints is frictional slipping between the connected members.² The slip may be translational or rotational. It may be slip-stick or stictional. Furthermore, the slip may be on either the micro or macroscopic level, per Reference 2.

As force is applied to a joint, small regions of the interface area will break free and undergo *microslip*. This motion occurs only over a very small interface region, without relative displacement between the members.

As the force applied to the joint increases, larger portions of the interface will break free, eventually resulting in *macroslip* with relative displacement between the members.

Most engineering structures excited at reasonable levels will only ever experience microslip.

The friction and shear force between the slipping members causes energy dissipation by heat. Most references consider this to be Coulomb or dry friction³, but the frictional force may follow other patterns such as stiction⁴ or Stribeck per Reference 9. Note that frictional effects are represented on force-velocity curves.

¹ These other forms may include plastic deformation of the material, air or structural-borne sound radiation, boundary interactions and aerodynamic drag

² The members also have material damping. Nevertheless, joint friction is a greater damping source than material damping, per References 8 and 9. Furthermore, air pumping at joints has also been identified as an energy loss mechanism in Reference 1, but this type of damping is more a concern if one of the members is a plate. This tutorial is mainly concerned with the case where the connected members are beams. Finally, aerodynamic drag is negligible per Reference 8.

³ A simple mathematical example is given in Reference 10.

⁴ Stiction is a model whereby static friction is higher than kinetic friction.

Bolted Joints

The amount or energy loss for a bolted joint depends on the materials, surface finish, contact area, bolt tension, lubrication, fretting corrosion, etc. Note that the joint becomes stiffer with less damping as the bolt torque increases, per Reference 4.

Two types of bolted joints are considered in Appendix A, as taken from Reference 3. The first is a bearing connection. The second is a friction connection. The bearing type allows for greater slip and hence has greater damping, as discussed later in this report.

Welded Joints

Some interfacial friction damping effects also occur in welded joints, but welded joints are much stiffer than the bolt-joints. Welded joints may thus have small damping ratios than bolted joints, as shown by empirical data presented later in this tutorial.

Damping Measurement

The resulting energy loss in a frictional joint for harmonic motion can be measured by the area within the hysteresis plot of force vs. displacement. This requires that a force transducer be inserted between the applied force and the joint. It also requires double integrating the accelerometer results to obtain displacement.

A simpler method is to mount one or more accelerometers on the test item, and then to subject the item to an impulse force or an initial displacement. The decay in the accelerometer time histories can then be modeled in terms of equivalent viscous damping using the *peak amplitude* method, as described in Reference 2.

Non-linearity

Damping tends to increase as the excitation level increases, per the data from References 2 and 7 given later in this report. The explanation is that a greater amount of slipping occurs as the response level increases. Again, the corresponding friction increases the damping.

U.S. Nuclear Regulatory Commission Damping Values

The U.S. Nuclear Regulatory Commission gives the damping ratios in Table 1 for nuclear plant structures, as taken from Reference 5. The values are intended for analysis purposes when measured damping values are unavailable.

Table 1. Damping Values for Steel Buildings, Operating-Basis Earthquake	
Joint Type	Damping Ratio
Welded Steel or Bolted Steel with Friction Connections	3%
Bolted Steel with Bearing Connections	5%

Note that friction connections have the same value as welded joints in Table 1.

Australian/New Zealand Structural Design Standard Damping Values

Reference 6 gives the recommended damping values shown in Table 2. The reference does not distinguish between the types of bolted joints.

Joint Type	Damping Ratio
Welded Joints	2%
Bolted Joints	5%

Sandia Experimental Data, Beam Test

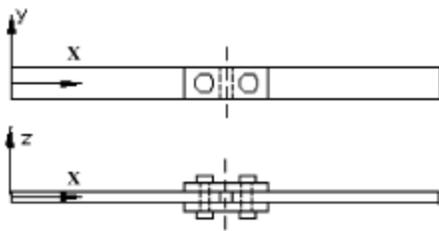


Figure 1. Jointed Beam

A team of engineers led by Sandia National Laboratories performed some joint damping experiments as documented in Reference 2. Two beams were tested.

The first was the jointed beam in Figure 1, with dimensions of 20.25 inch x 1 inch x 0.25 inch. The second was a monolithic beam with the same dimensions.

The material for each beam was low-carbon steel.

Free boundary conditions were simulated in the tests by suspending the beams at their two ends from the ceiling with a 6 ft long length of nylon cord.

Each beam was excited by an impulse hammer. The response was measured by accelerometers mounted on the beams. The input force was varied to determine the non-linearity of the damping ratio.

The fundamental frequencies of the jointed and monolithic beams were 132 and 139 Hz, respectively.

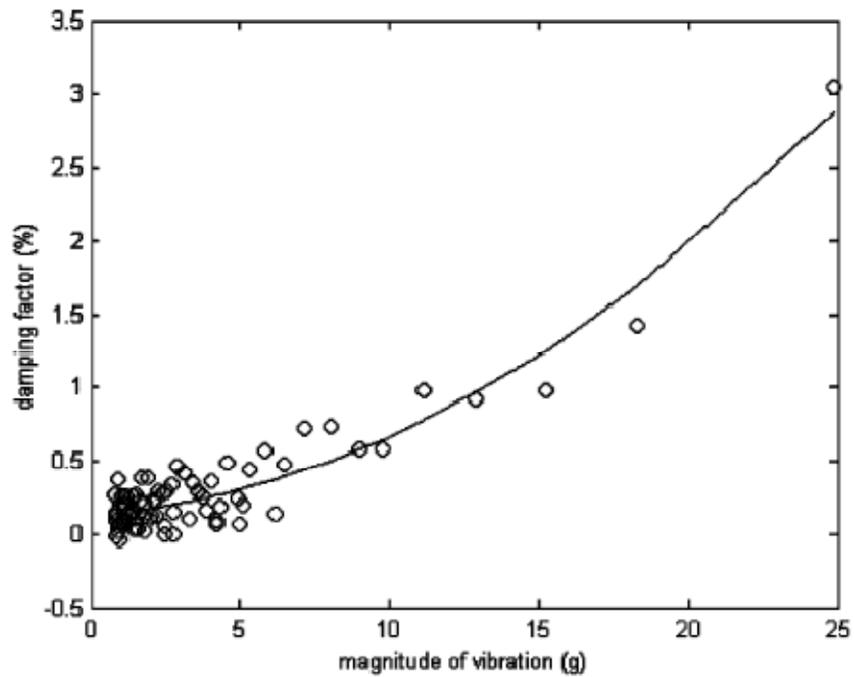


Figure 2. Equivalent Viscous Damping Ratio vs. Vibration Magnitude for the First Mode of the Jointed Beam

The marker symbols represent experimental data. The solid curve is a fitted function.

The researchers from Reference 2 concluded from the data that the damping at the joint is non-viscous at high amplitudes.

As the amplitude diminishes, the non-linear frictional effects are eliminated and the system approaches viscous damping.

Sandia Experimental Data, Frame Test

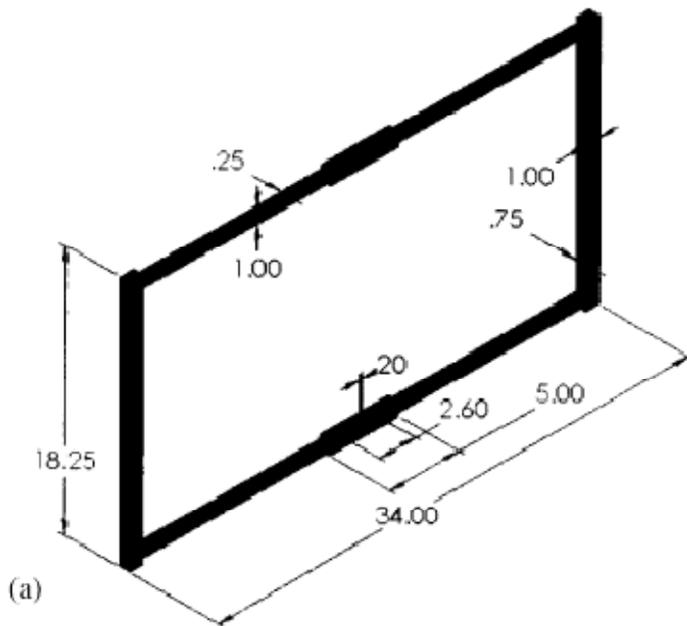


Figure 3. Frame

Sandia engineers also designed the rectangular frame shown in Figure 3, as given in Reference 2.

Two frames were built. The jointed frame consisted of the frame with a cut in one of its longitudinal beams. Two lap plates were mounted at the cut via bolts to join the members together.

The second frame was monolithic. It was manufactured to the same dimensions, but the plates were welded onto the cut leg of the frame, in place of the bolted joint.

Note that that the corners of both frames were also welded together.

Also, a lumped mass consisting of two plates was welded onto the center of one of the longitudinal beams for each frame.

Each structure was suspended using two 6 ft lengths of nylon cord, in an effort to simulate free boundary conditions.

A series of hammer tests was performed to identify the natural frequencies and modal damping ratios of the jointed and monolithic frames with free boundary conditions. The results are shown in Table 3.

Table 3. Frame Test Results, Fundamental Mode		
Frame	f_n (Hz)	Damping Ratio
Jointed	24.3	0.04%
Monolithic	24.6	0.12%

The authors of Reference 2 concluded that the welded corners did not exhibit much microslip

Babol Noshirvani University Students' Experimental Results

The following data is taken from Reference 7.



Figure 4. Frame System

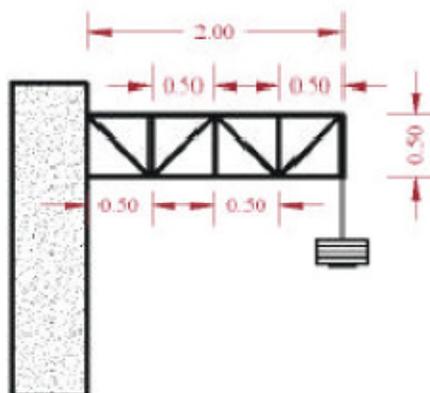


Figure 5. Dimensions in meters

The students erected two frame structures, as shown in Figure 4. The systems were identical except that one had welded joints while the other had bolted joints. The reference did not state the material type, but it was presumably steel. The reference also did not state whether the bolted joints were the bearing or frictional type.

The frame structures were subjected to an initial static load by attaching weights via a wire rope cable to the free end of the structure, as shown in Figure 5. This force subjected each structure to an initial displacement. The wire cable was then cut, causing the structure to oscillate as it tried to return to its unloaded equilibrium condition.

Accelerometers were mounted on the structures to measure each response and corresponding damping ratio. The reference did not give the natural frequency explicitly, but a time history plot in the reference shows that the welded structure had a fundamental frequency of about 30 Hz.

Joint Type	12.5 kg	25 kg	37.5 kg	50 kg	62.5 kg	75 kg	Average
Welded	1.2%	1.3%	1.3%	1.4%	1.9%	2.2%	1.5%
Bolted	2.2%	3.3%	3.8%	4.1%	4.7%	5.3%	3.9%
Bolted/Welded	1.9	2.5	2.8	3.0	2.5	2.5	2.5

The students were able to assess the damping linearity by applying various initial loads, as shown in Table 5.

The initial load is represented by the kg value. The damping ratios are expressed as percentages.

The welded joint structure's damping ratio varied from 1.2 to 2.2%.

The bolted joint structure's damping ratio varied from 2.2 to 5.3%.

On average, the bolted joint had a damping value that was 2.5 times greater than that of the welded joint.

Conclusions

Structural joint damping has a non-linear effect. The amount of damping tends to increase with higher dynamic loads or higher initial displacements due to increased slip.

Structural joint damping occurs due to the frictional effects which accompany slipping. Both welded and bolted joints can experience microslip, as evidenced by the non-linearity in damping measurements of joined structures.

In some cases, bolted joints may also experience macroslip, where the connected members have a relative displacement between themselves.

Bolted joints have a damping ratio that is potentially 2 to 3 times higher than welded joints, because bolted joints can experience greater slip.⁵

Bearing bolted joints have a higher potential damping ratio than friction bolted joints, because bearing joints allow for greater slip, at least until the bolt clamping force in the friction joint is overcome by the shear force between the members.

References

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⁵ Larger slip is desirable for damping, but it can lead to fretting corrosion.

APPENDIX A

BOLTED JOINTS TYPES

The following sections are taken from Reference 3.

Force Transfer of Bearing Type Bolts

The free body diagram of the shear force transfer in bearing bolt connection is shown in Figure A-1. The tension in one plate is equilibrated by the bearing stress between the bolt and the hole in the plate.

There is an initial clearance between the bolt and the hole in which it is fitted. The bearing stress becomes active only after the plates slip relative to one another and start bearing on the bolt.

The section $x-x$ in the bolt is critical section for shear. There is only one critical section in shear (single shear) in the bolt since the joint is a lap joint.

In the case of butt splices, there would be two critical sections in the bolt in shear (double shear), corresponding to the two cover plates.

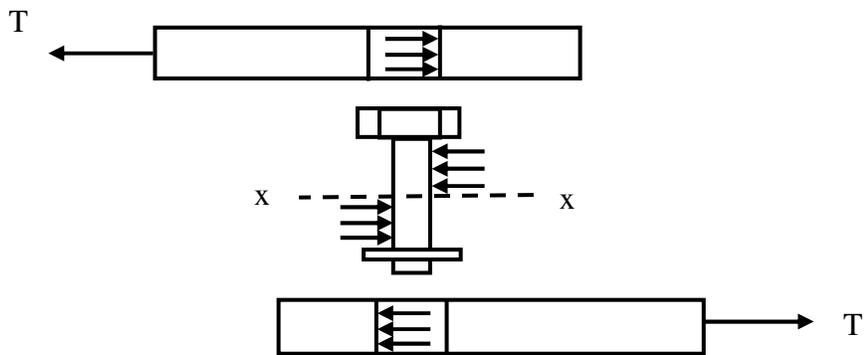


Figure A-1. Shear Transfer by Bearing Bolt

The arrows indicated bearing forces.

High Strength Friction Grip (HSFG) Bolts

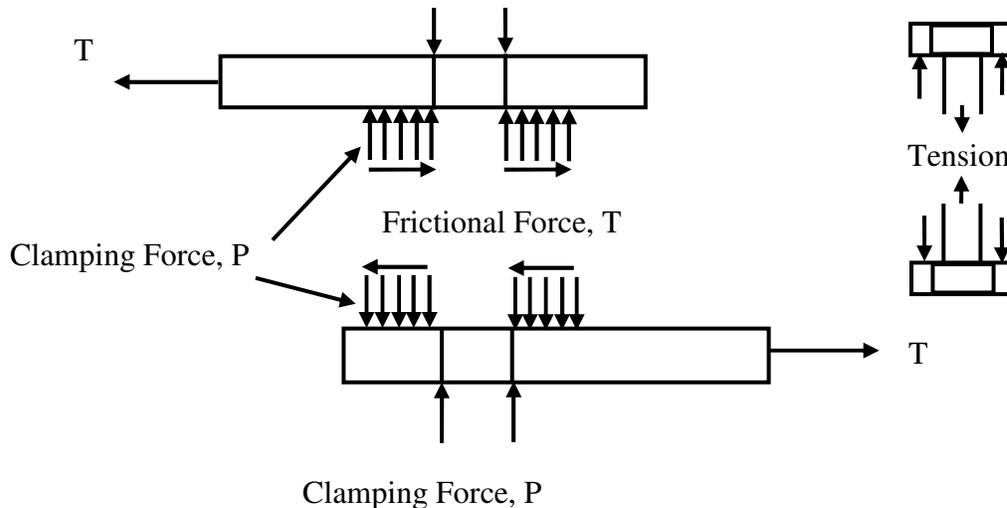


Figure A-2. Shear Transfer in a Friction Joint

The free body diagram of an HSFG connection is shown in Figure A-2.

The pretension in the bolt causes clamping forces between the plates before the external load is applied. When the external load is applied, the tendency of two plates to slip against one another is resisted by the friction between the plates. The frictional resistance is equal to the coefficient of friction multiplied by the normal clamping force between the plates.

The HSFG connections are designed such that under service load the force does not exceed the frictional resistance so that the relative slip is avoided during normal service.

Now consider that the service load has been exceeded. When the external force exceeds the frictional resistance, the plates slip until the bolts come into contact with the plate and start bearing against the hole. Beyond this point the external force is resisted by the combined action of the frictional resistance and the bearing resistance.