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**VIRTUAL ANALYSIS OF EFFECT OF DAMPING IN DIFFERENT MATERIAL
LAYERED BEAM USING STRUCTURAL JOINTS**

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ABSTRACT

In Engineering Vibration and noise reduction are crucial in maintaining high performance level and prolong use. Structures are generally fabricated using a variety of shear connectors such as bolts, rivets, etc. The joints play a significant role in the overall system behaviour. Particularly the damping level of the structures occurs due to energy release due to micro slip along frictional interface between two surfaces, and also because of varying strain region. Some parameter such as end condition, type of joints, number of joints used in structure play significant role in structural vibration analysis. This work was carried out to study effect of number of joints and thickness of layer on material damping with particular end condition. Analysis was carried on various combination of number of bolts and rivets with Aluminium and Mild Steel beam. Using FEA model, natural frequency of various combinations of structural joints was calculated. Various simulations were performed in SOLIDWORKS. The natural frequencies, logarithmic decrement and damping factor of riveted and bolted joints were calculated. The evaluated theoretical and simulation results were utilised for comparison.

Keywords: Material damping, Structural damping, Structural joints, Layered beam.

INTRODUCTION

Damping is the energy dissipation properties of a material or system under cyclic stresses. When a structure is subjected to an excitation by an external force then it vibrates in certain amplitude of vibration, it reduces as the external force is removed. This is due to some resistance offered to the structural member which may be internal or external. This resistance is termed as damping. The origin and mechanism of damping are complex and sometimes difficult to comprehend. The energy of the vibrating system is dissipated by various mechanisms and often more than one mechanism may be present simultaneously.

Structural damping is widely used for creating of many structures. Although an ample amount of work has been reported on the study of damping in rivet and bolt structures with non-uniform pressure distribution at the interfaces, Less generalized theory has been established for these beams with uniform pressure distribution at the interfaces. Most engineering designs are built up by connecting structural components through mechanical connections. Such assembled designs need sufficient damping to limit excessive vibrations under dynamic loads. Damping in such designs mainly starts from two sources. One is the internal or material damping which is innately low [1] and the other one is the structural damping due to joints [2]. The behind one offers a best source of energy dissipation, thereby sufficiently compensates the low material damping of structures. It is estimated that structures consisting of bolted or riveted members contribute about 90% and rest by others of the damping through the joints [3]. The arrangement of layers in association with joints encourages large damping in built-up structures. These connections are identified as a good source of energy dissipation and mostly affect the dynamic behaviour in

terms of natural frequency and damping [4]. This structural damping offers excellent potential for large energy dissipation is associated with the interface shear of the joint. It is thus identified that the provision of joints can effectually contribute to the damping of all fabricated structures. Although most of the damping occurring in real structures arises in the joints, but a little effort has been made to study this source of damping because of complex mechanism occurring at the interfaces due to relative slip, coefficient of friction and pressure distribution characteristics. It is therefore important to focus the contemplation to study these parameters for accurate assessment of the damping capacity of structures.

Recently, Singh and Nanda proposed a method to evaluate the damping capacity of tack welded structures. They established that with the increase in the number of tack welds the damping capacity decreases [10]. Nanda and Behera have also done considerable amount of work on the distribution pattern of the interface pressure and have found out the damping capacity of such layered and jointed structures both numerically and experimentally considering various parameters. Moreover, they conducted experiments to study the nonlinear effects of a typical shear lap joint on the dynamics of two structures: a beam with a bolted joint in its centre; and a frame with a bolted joint in one of its members. Pavan Kumar [12] have also done considerable amount of work on effect on damping of machine tool structure with riveted joint.

Objective of present work was to study effect in damping ratio of structural joints with dissimilar material having same thickness ratio for Fixed-Fixed boundary condition.

MATERIALS AND METHODS

Theory Of Beams Of Two Materials :-

Beams of two parts are often used in structural system to take advantage of different properties of the two materials. For example, in reinforced concrete beams, the concrete is strong in compression but very weak in tension, so beam is reinforced with steel to enable it to resist tension stress caused by bending.

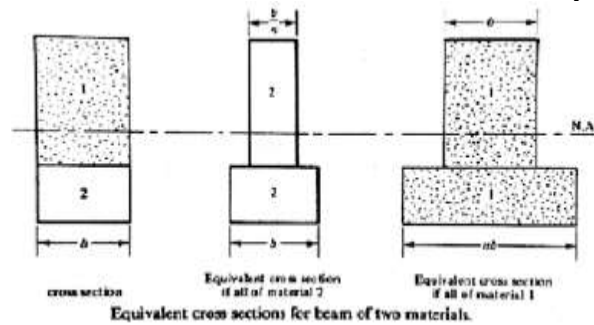


Figure 2. Equivalent Cross-Section For Beam Of Two Material

As an example, consider the composite cross section shown in fig. 2(a). Assuming that $E_1 < E_2$ and that $E_2/E_1 = n$, both the possible transformed cross section are as shown in the figure. Note that in each case only dimensions parallel to the neutral axis have been changed to obtain the respective equivalent areas.

The mass per unit length of the composite beam of the two materials as shown in figure 1 is

$$\gamma = \rho_1 A_1 + \rho_2 A_2 \tag{1}$$

In which the ρ_1 & ρ_2 are the mass densities of materials. Since the maximum velocity of any cross section of the beam is $y\omega_n$, the maximum kinetic energy of the beam is

$$T_{max} = \frac{\rho_1 A_1 + \rho_2 A_2}{2} \int_0^1 (y\omega_n)^2 dx \tag{2}$$

In which $y = f(x)$ is the shape function used.

It can be shown that $E_1 I_1 + E_2 I_2 = E_c I_c$ in which E_c is the elastic modulus of the transformed cross section material, & I_c is the area of moment of inertia of the transformed cross section about neutral axis.

Dynamic Equitation For Free Transverse Vibration On Various Joint Structures :-

The beam vibration is governing by partial differential equation in terms of spatial variable x & time variable t . Thus, the governing equation for free vibration is given by:

$$E_c I_c \frac{d^4 y}{dx^4} + \rho_e A \frac{d^2 y}{dt^2} = 0 \tag{3}$$

Where, E_c, I_c, ρ_e & A are Equivalent modulus of elasticity, second Equivalent moment of area of the beam, Equivalent mass density & cross sectional area of beam respectively.

The free vibration given in equation 8 contains four spatial derivatives & hence requires four boundary conditions for getting solution. The presence of two time derivatives again requires two initial conditions, one for displacement & another for velocity. Eq.3 is solved by method of separation of variables. The displacement $y(x,t)$ is written as the product of two functions, one depends only on x and the other only on t . Thus the solution is expressed as:

$$y(x,t) = X(x) * F(t) \tag{4}$$

Where $X(x)$ & $F(t)$ are the space & time function respectively.

Substitute eq. 4 & rearrange result:

$$E_c I_e F(t) \frac{d^4 x}{dx^4} = -\rho_e A X(x) \frac{d^4 t}{dt^4} \tag{5}$$

Divide eq. 4-5 by $X(x) F(t)$ on both sides, variables are separated as;

$$\frac{d^4 t}{dt^4} = - \frac{E_c I_e}{\rho_e A} \frac{d^4 x}{dx^4} = \omega_n^2 \tag{6}$$

Where the term ω_n^2 is the separation constant, representing the square of natural frequency.

This equation yields two order differential equations.

The first one is given as;

$$\frac{d^4 x}{dx^4} - \lambda^4 X(x) = 0 \tag{7}$$

$$\text{Where, } \lambda^4 = \frac{\rho_e A}{E_c I_e} \omega_n^2 \tag{8}$$

The required solution of eq. 8 is simplified as;

$$X(x) = A_1 \sin \lambda x + A_2 \cos \lambda x + A_3 \sinh \lambda x + A_4 \cosh \lambda x \tag{9}$$

Where constant A_1, A_2, A_3 & A_4 are determined from boundary conditions of fixed-fixed beam.

This is the similar free vibration expression for an un-damped single degree of freedom system having the solution

$$T(t) = A \cos \omega_n t + B \sin \omega_n t \tag{10}$$

Dynamic equation for rivet joints is expressed by inserting the values of A & B

$$y(x,t) = Y(x) \frac{y_0}{y(\frac{L}{2})} \cos \omega_n t \tag{11}$$

Substituting the expression for space & time function as given by eq. 9 & eq. 10 into eq. 11, the complete solution for the deflection of a beam at any section is expressed as;

$$y(x,t) = (A_1 \sin \lambda x + A_2 \cos \lambda x + A_3 \sinh \lambda x + A_4 \cosh \lambda x) * (A_5 \cos \omega_n t + A_6 \sin \omega_n t) \tag{12}$$

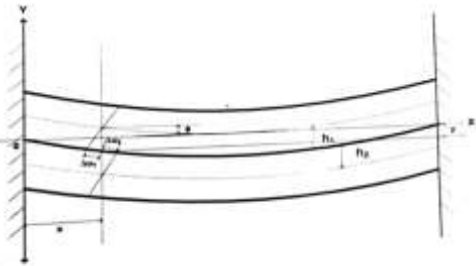


Figure 3. Mechanism of slip at interface

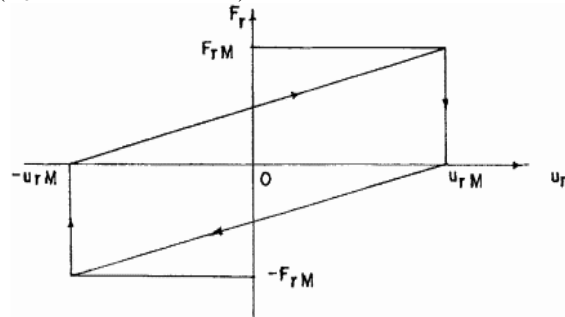


Fig. 4. Relationship between the friction force (F_r) and the relative dynamic slip (u_r) during one cycle.

Evaluation of Constant A_1, A_2, A_3 & A_4

Applying the boundary condition for fixed-fixed beam given as,

$$\begin{array}{lll} \text{At } x = 0; & X(0) = 0; & X'(0) = 0; \\ \text{At } x = L; & X(L) = 0; & X'(L) = 0; \end{array}$$

These equations can be represented in a matrix form as;

$$\begin{bmatrix} 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ \sin \lambda L & \cos \lambda L & -\sinh \lambda L & \cosh \lambda L \\ \cos \lambda L & -\sin \lambda L & \cosh \lambda L & \sinh \lambda L \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

To get a non-trivial solution, setting the determinant equal to zero;

$$\begin{vmatrix} 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ \sin \lambda L & \cos \lambda L & -\sinh \lambda L & \cosh \lambda L \\ \cos \lambda L & -\sin \lambda L & \cosh \lambda L & \sinh \lambda L \end{vmatrix} = 0$$

The constant A_2, A_3 & A_4 are dependent parameter but A_1 is an independent parameter. A_1 may have any values. Taking $A_1=1$, values of A_2, A_3 & A_4 are found as;

$$A_2 = \left(\frac{\sinh \lambda l - \sin \lambda L}{\cos \lambda L - \cosh \lambda L} \right); \quad A_3 = -1; \quad A_4 = - \left(\frac{\sinh \lambda l - \sin \lambda L}{\cos \lambda L - \cosh \lambda L} \right); \quad A_1 = 1 \tag{13}$$

Now space function given by eq. 5 is modified as;

$$X(x) = \sin \lambda x + \left(\frac{\sinh \lambda l - \sin \lambda L}{\cos \lambda L - \cosh \lambda L} \right) \cos \lambda x - \sinh \lambda x - \left(\frac{\sinh \lambda l - \sin \lambda L}{\cos \lambda L - \cosh \lambda L} \right) \cosh \lambda x \tag{14}$$

$$\text{i.e., } X(x) = \frac{(\sinh \lambda x - \sin \lambda x)(\cos \lambda L - \cosh \lambda L) + (\cos \lambda x - \cosh \lambda x)(\sinh \lambda L - \sin \lambda L)}{(\cos \lambda L - \cosh \lambda L)} \tag{15}$$

This equation gives the different mode shapes of vibration.

$$y(x,t) = \left[\begin{matrix} (\sinh \lambda x - \sin \lambda x)(\cos \lambda L - \cosh \lambda L) \\ + (\cos \lambda x - \cosh \lambda x)(\sinh \lambda L - \sin \lambda L) \end{matrix} \right] \left[\begin{matrix} y(\frac{l}{2}, 0) \\ x(\frac{l}{2}) \end{matrix} \right] \left[\begin{matrix} \cos \omega_n t \\ (\cos \lambda L - \cosh \lambda L) \end{matrix} \right] \tag{16}$$

This is the generalized deflection equation at any section of Fixed –Fixed beam.

Evaluation Of Relative Dynamic Slip :

The relative slip at the interface in the presence of friction during the vibration is given as;

$$u_r(x,t) = \alpha u(x,t) = 2 \alpha h \tan \left[\frac{\partial y(x,t)}{\partial x} \right] \tag{17}$$

Where α = slip ratio; h = thickness of the beam

$y(x,t)$ = deflection at a distance ‘x’ from the fixed end

$u(x,t)$ = dynamic slip without friction

Analysis Of Energy Dissipated :

The energy is dissipated due to the friction & relative dynamic slip at the interface is given by;

$$E_{loss} = 2 \left\{ \int_0^{\frac{\pi}{\omega_n}} \left\{ \int_0^{\frac{L}{2}} \mu p b \left[\frac{\partial u_r(x,t)}{\partial t} \right] dx \right\} dt \right\} \tag{18}$$

Where μ = coefficient of kinematic friction

p = uniform pressure distribution at the interface

L = Length of beam

ω_n = Natural frequency of vibration

The strain energy per half cycle of vibration is given by;

$$E_{ne} = \left(\frac{192 E_{eq} I_{eq}}{L^3} \right) y^2 \left(\frac{l}{2}, 0 \right) \tag{19}$$

Where E_{eq} is the equivalent modulus of elasticity, I_{eq} is cross section equivalent moment of inertia & $y(l/2, 0)$ is transverse deflection at the midpoint of the fixed-fixed beam for rivet respectively

$$\frac{E_{LOSS}}{E_{NET}} = \left[\frac{8 \mu b h p \alpha y \left(\frac{l}{2}, 0 \right)}{192 \left(\frac{E_{eq} I_{eq}}{L^3} \right) y^2 \left(\frac{l}{2}, 0 \right)} \right] \tag{20}$$

Where k_f is the bending stiffness of fixed fixed beam.

Similarly the energy dissipated for bolted joints and the energy loss due to frictional force at the interface per half cycle of vibration is given by,

$$E_{loss} = \int_0^{\frac{\pi}{\omega_n}} \int_0^1 \mu p b \left[\left\{ \frac{\partial u_r(x,t)}{\partial t} \right\} dx \right] dt \tag{21}$$

Evaluation Of Damping Ratio :-

The damping ratio ψ , is expressed as the ratio of energy dissipated due to the relative dynamic slip at the interface and the total energy introduced in to the system for rivets is found to be,

$$\psi = \left[\frac{E_{loss}}{E_{loss} + E_{net}} \right] = \frac{1}{\left[1 + \frac{E_{net}}{E_{loss}} \right]} \tag{22}$$

where E_{loss} and E_{net} are the energy loss due to interface friction and the energy introduced during the unloading process . Putting the values of $\frac{E_{Loss}}{E_{Net}}$, we get

$$\psi = \frac{1}{\left[1 + \frac{ky(\frac{L}{2},0)}{[sbph\alpha\mu]} \right]} \tag{23}$$

$$\psi = \frac{1}{\left[1 + \frac{ky(\frac{L}{2},0)}{[2bph\alpha\mu]} \right]} \tag{24}$$

The above Equations are used for calculating the damping ratio for the three jointed structures.

Logarithmic Decrement:-

Logarithmic Decrement (δ), a measure of damping capacity, is defined as the natural logarithm of the ratio of two consecutive amplitude in a given cycle

$$\delta = \frac{1}{n} \ln\left(\frac{x_0}{x_n}\right) \tag{25}$$

where x_0 - amplitude of vibration of first cycle ,
 x_n - amplitude of vibration of last cycle ,
 n- number of cycles

Logarithmic decrement also written as;

$$\delta = \frac{1}{2} \frac{E_{LOSS}}{E_{NET}} \tag{26}$$

The logarithmic decrement for Riveted Joint is given as;

$$\delta = \frac{1}{n} \ln\left(\frac{a_n}{a_{n+1}}\right) = \left[\ln\left\{ \frac{1}{1-\psi} \right\} \right] / 2 \tag{27}$$

By simplifying the above equation we get

$$\delta = \frac{1}{2} \ln\left[1 + \frac{8\mu b h p \alpha}{k_{eq,y}\left(\frac{L}{2},0\right)} \right] \tag{28}$$

simplifying the logarithmic decrement for bolted joints $\mu\alpha$ is assumed to be constant and has been found out from the experimental results for logarithmic damping decrement as

$$\delta = \frac{1}{2} \ln\left(1 + \frac{8\alpha\mu p b h}{k_{eq,y}\left(\frac{L}{2},0\right)} \right) \tag{29}$$

$$\delta = \left[\frac{2\mu b h p \alpha y\left(\frac{L}{2},0\right)}{K_s y^2\left(\frac{L}{2},0\right)} \right] \tag{30}$$

Where, K_s is Equivalent Static Spring Stiffness.

MODELLING AND ANALYSIS

Modelling :-

In this paper, a models was prepared using SOLIDWorks .The 9 models were prepared as standard case in which aluminium and Mild Steel plates are joined using a riveted joint & Bolted joints and were discussed thoroughly. An assembled view of this model is shown in figure 5 and figure 6.

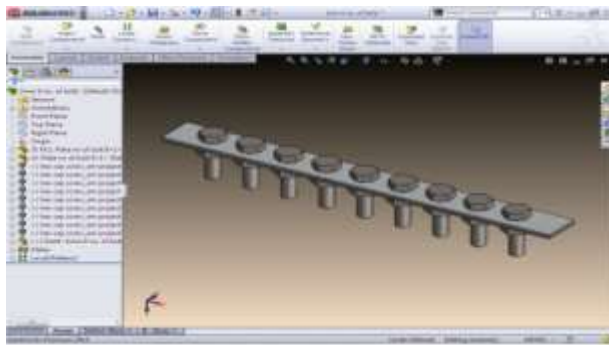


Figure 5. Model of Bolted Joint designed in SOLIDWorks.



Figure 6. Model of Riveted Joint designed in SOLIDWorks.

Natural Frequency Analysis :-

Frequency analysis, also known as modal or dynamic analysis, calculates the resonant (natural) frequencies and the corresponding mode shapes. Hence it is known as Natural Frequency Analysis as shown in figure 7 and Figure 8.

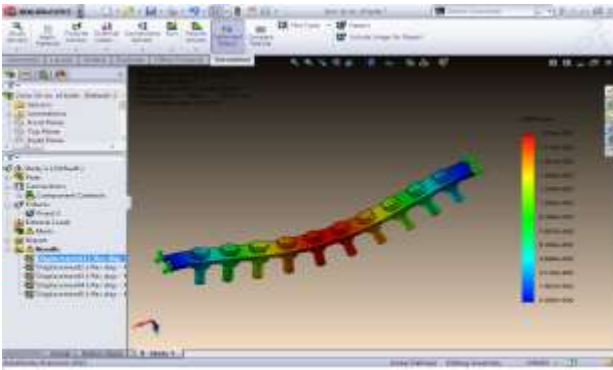


Figure 7. Natural Frequency Analysis of Bolted Joint.

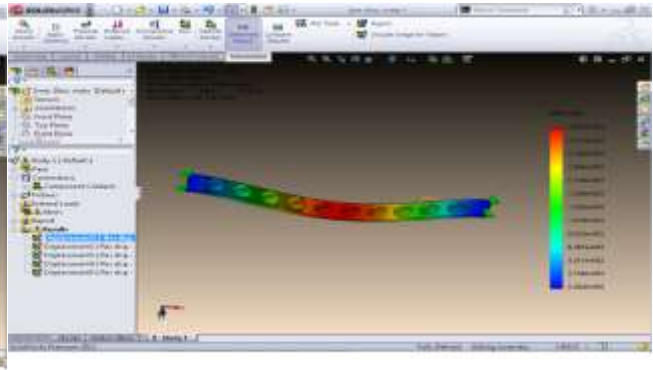


Figure 8. Natural Frequency Analysis of Riveted Joint.

The results and discussion may be combined into a common section or obtainable separately. They may also be broken into subsets with short, revealing captions.

COMPARISON OF RESULTS AND DISCUSSION

The logarithmic decrement of two layer of riveted as well as bolted joint have been find out using expression (27) and (30). The specimen are prepare for analysis from commercial Mild Steel and Aluminium flat of sizes as present in table 1. The distance between to joint have been kept 2.8 times the diameter of bolt or rivet

Table 1
 Details Of Specimen Used For Analysis Of Bolted And Riveted Joint.

Thickness Of Plate (mm)	Plate Material Combination	Width Of Plate (mm)	Diameter Of The Connector (mm)	Number Of Layers	Number Of Connector	Total Plate Length (mm)
2	Aluminum Mild Steel	28	10	2	9	280
					10	308
					12	364
3		28	10	2	9	280
					10	308
					12	364
5		28	10	2	9	280
					10	308
					12	364

From the theoretical analysis as well as solidworks analysis result are drawn as detailed below.

Results For Mode Shape Vs. Natural Frequency :-

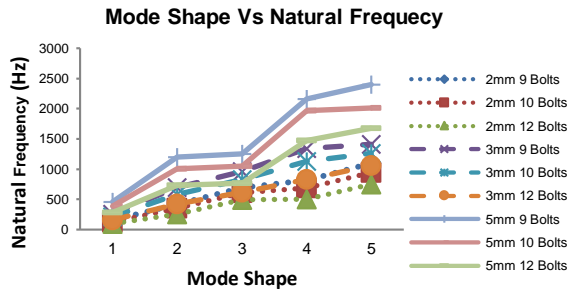


Figure 9. Variation in natural frequency for different mode shape for fixed beam in bolted joint

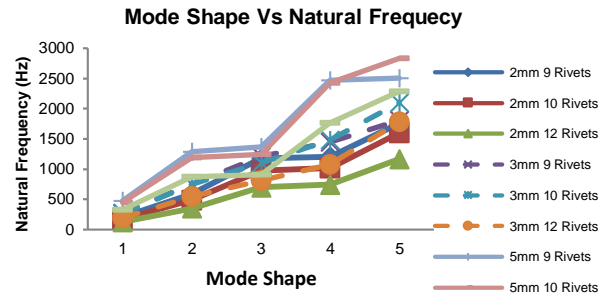


Figure 10. Variation in natural frequency for different mode shape for fixed beam in riveted joint

Results For Thickness Of Beam Verses Logarithmic Decrement :-

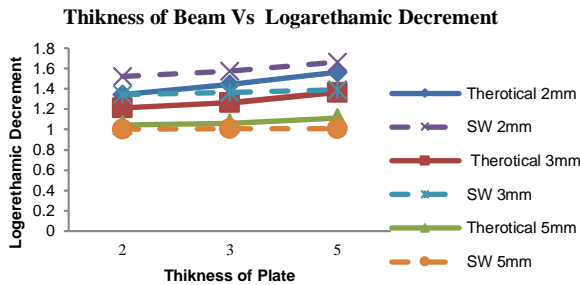


Figure 11. Variation in Logarithmic decrement for different thickness of beam for fixed beam in bolted joint

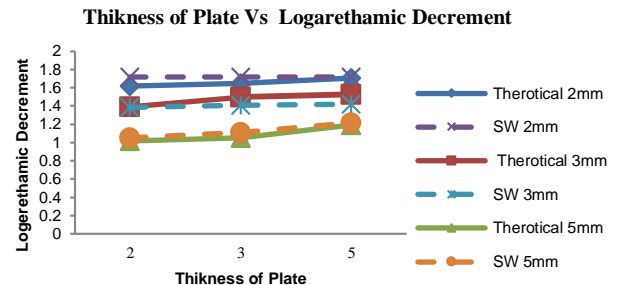


Figure 12. Variation in Logarithmic decrement for different thickness of beam for fixed beam in riveted joint

Results For No. Of Connectors Verses Logarithmic Decrement :-

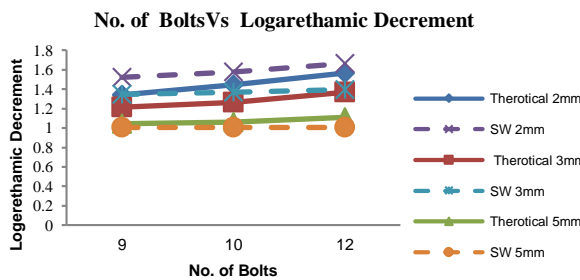


Figure 13. Variation in Logarithmic decrement for different No. of connectors for fixed beam in bolted joint

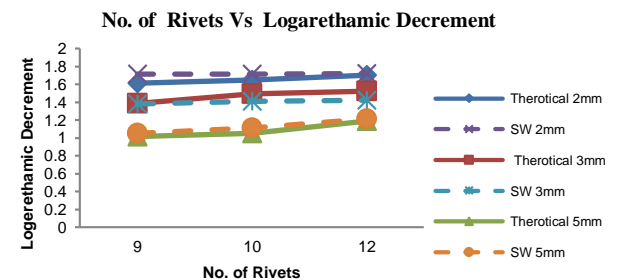


Figure 14. Variation in Logarithmic decrement for different No. of connectors for fixed beam in riveted joint

Results For Thickness Of Beam Verses Damping Ratio :-

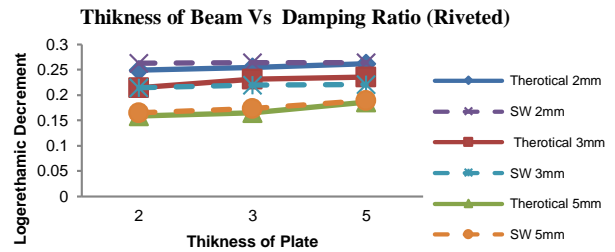
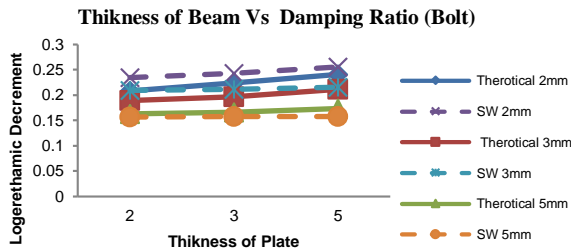


Figure 15. Variation in Damping ratio for different thickness of beam for fixed beam in bolted joint

Figure 16. Variation in Damping ratio for different thickness of beam for fixed beam in riveted joint

Results For Total Span Of Beam Verses Damping Ratio:-

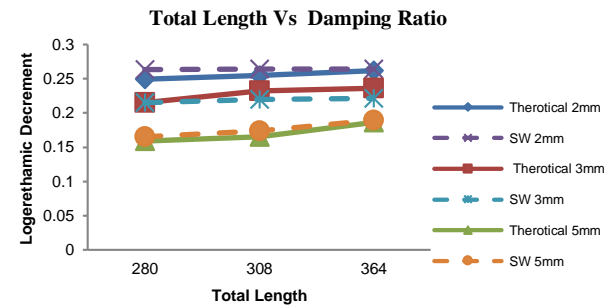
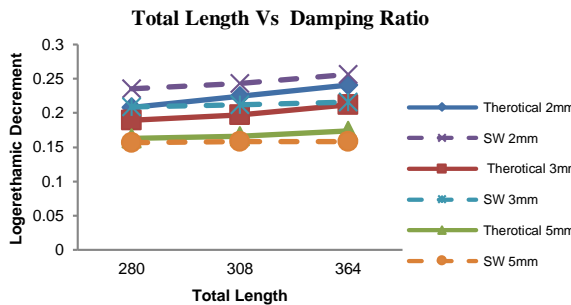


Figure 17. Variation in Damping ratio for different total span of beam for fixed beam in bolted joint

Figure 18. Variation in Damping ratio for different total span of beam for fixed beam in riveted joint

Results For No. Of Connectors Verses Damping Ratio:-

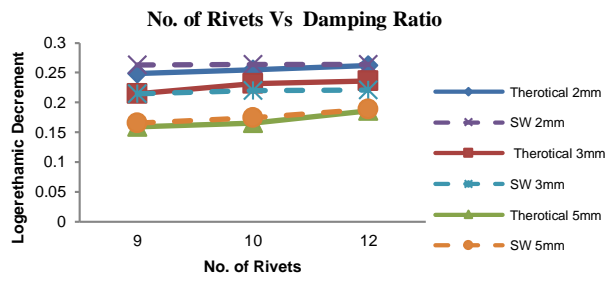
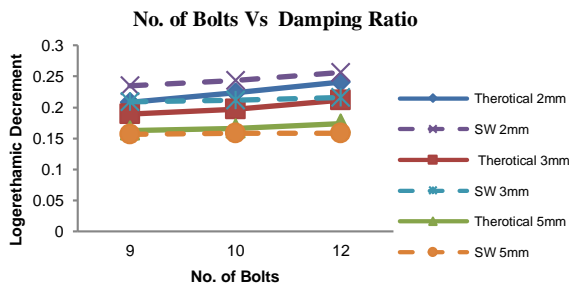


Figure 19. Variation in Damping ratio for different no. of connector for fixed beam in bolted joint

Figure 20. Variation in Damping ratio for different no. of connector for fixed beam in riveted joint

DISCUSSION :-

1. Damping ratio in jointed structure increase with increase in length. Increase in length result in an enlarge the surface length. Thus the amplified area for energy dissipation of the structure is increases and more contact area results more energy dissipation.
2. Damping ratio inverses with rise in number of connectors.

3. Damping ratio decreases as the beam thickness increases. The increase in thickness results reduce in logarithmic decrement also.
4. The interface pressure distribution and relative space of the successive connecting bolts and rivets are found to play important role on the damping capacity of the structure.

CONCLUSION

Damping in structure occur due to friction and micro-slip between interfaces. The primary source to improve damping are automated joints and fasteners.

From the prior discussion it is found that the damping of bolted and riveted structure can be eliminated by following influence parameter –a) Frequency of vibration, b) length of specimen, (c) end condition of the beam specimen, (d) pressure distribution, (e) thickness of beam.

The interface pressure distribution and relative space of the consecutive connecting bolts and rivets are found to play major role on the damping capacity of the structure.

There is decrease in static bending stiffness with increase in total length of specimen, so that the strain energy presented into the system is decline. An increase in amplitude of vibration results in more input strain energy to the system

From the values obtain from theoretical analysis as well as SolidWorks analysis concludes that the damping capacity is higher in bolted joint rather than riveted joint.

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