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Studies on Vibration Damping of Steel Structures

Etudes sur l'amortissement des vibrations dans les structures en acier

Studie über Dämpfung von Vibrationen an Stahltragwerken

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1. Introduction

Properties of vibration damping of actual structures were mainly determined by field observations. The investigations, however, are usually limited to vibrations with very small amplitude. The damping properties necessary for structural design for dynamic loads must be corresponded to the actual loading conditions of the structures. Theoretical investigations, frequently, give more valuable information on this than limited field investigations.

In this paper, damping properties of steel structures, especially friction joints, within the elastic limit of the material were investigated by theoretical mean, and the relations between damping constants and amplitudes were obtained and given by specific formula. The model experiments were also done to examine the theoretical results.

If the effects of all sources of vibration damping are mutually exclusive, energy dissipation in one cycle of oscillation is given as,

$$\Delta W = \Delta W_1 + \Delta W_2 + \Delta W_3 + \cdots + \Delta W_n \tag{1}$$

where, ΔW_i indicates energy dissipation due to a specific source of vibration damping. If a specific number of sources in Eq. (1), say j, can be evaluated by theoretical or experimental means, energy dissipation obtained by the relation,

$$\Delta \underline{W} = \Delta W_1 + \Delta W_2 + \cdots + \Delta W_j \tag{2}$$

is always a lower bound of the real value ΔW. Damping constant computed by the equation,

$$\underline{\beta} = \frac{1}{4\pi} \frac{\Delta \underline{W}}{W} \tag{3}$$

is adoptable as a safe side value for practical dynamic design instead of real value β. Evaluation of specific source of vibration damping is important in this situation.

2. Preliminary Experiment

Fig. 1 shows the amplitude decay curves for two different model beams.[(1)] The first model has welded cross section and the vibration damping of this model is mainly due to material damping. The other model, the riveted beam, shows far rapid decay of amplitude since the damping due to mechanical friction is included in the model. Fig. 2 is more lucid expression of the results showing the relation between the damping constants and amplitudes. The riveted beam shows higher order property of damping than linear damping as in welded beam. If the source of damping is Coulomb type the damping constant and amplitude relation has to be decreased with amplitude as shown in the fine dotted line in Fig.2.

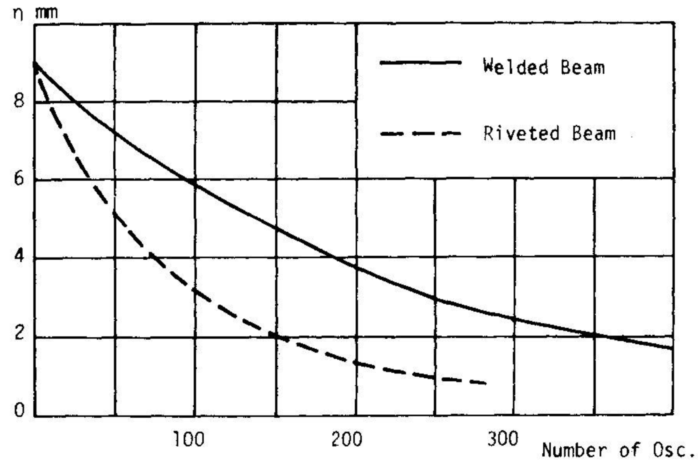

Fig.1

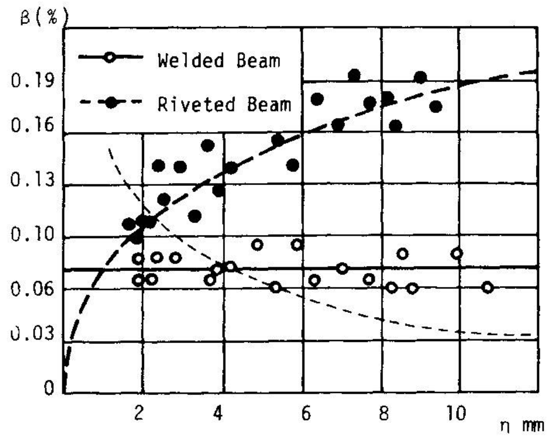

Fig. 2

According to the results given in Fig. 2, damping due to mechanical friction in riveted beam shows higher order damping than material damping and is not pure Coulomb damping. Damping due to mechanical friction of joints is explained by investigating the mechanism of energy dissipation as shown in the following.

3. Damping of Friction at Joint

Two kinds of method of analysis to obtain energy dissipation from friction joints are available. The first method was given by Pian and Hallowell[(2)] investigating the damping effect of a simple built-up beam. In this method, external load and deformation relationship during one cycle of loading was investigated, and the energy loss during the cycle was obtained. In the other method, given by Goodman and Klumpp[(3)], the energy loss was obtained directly by integrating partial slip multiplied by friction force.

Energy dissipation due to a cycle of loading for specific types of structural member and loading is investigated in this study by the first method, land the following results were obtained.

For the Case (a), Fig. 3,

$$\Delta W = \frac{48\,\kappa'\,M_{max}^3}{(1+2\kappa)^2 EI_c q_m t}$$

For the Case (b),

$$\Delta W = \frac{72(m+m^2)^2 F_{max}^3}{3(1+2\kappa)^2 EI_c q_m t} \cdot \left[\frac{(c+e)^3}{(1+\phi_o)^2} + \frac{(c-e)^3}{(1-\phi_o)^2}\right] - \frac{72(m+m^2)^2 c^3 F_{max}^3}{4\kappa^2 EI_c (1+2\kappa) q_m t} \cdot \left[\frac{1}{1+\phi_o} + \frac{1}{1-\phi_o}\right]$$

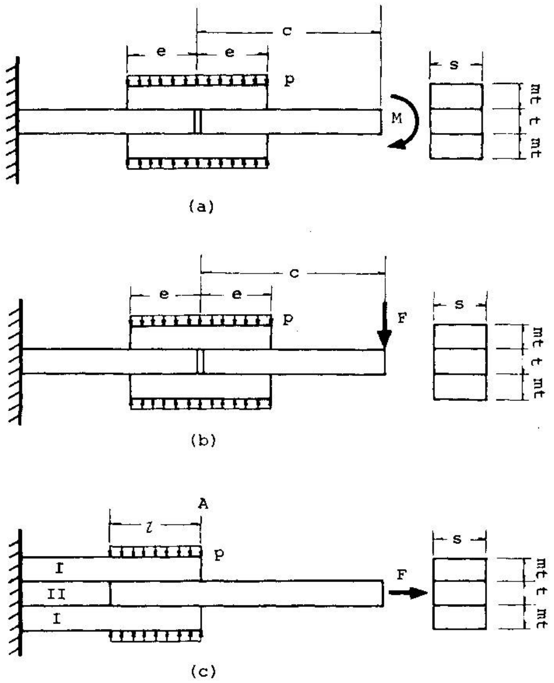

Fig. 3

where,

EI_c: equivalent stiffness

q_m : critical friction force

$\kappa = 3m + 6m^2 + 4m^3$

$$\kappa' = \frac{m+m^2}{\kappa^2}\left[2(m+m^2)^2\kappa^2 - \{1+(2-m-m^2)\kappa\}\right], \quad \phi_o = \frac{6(m+m^2)F_{max}}{(1+2\kappa)\,q_m t}$$

For Case (c),

$$\Delta W = \frac{2F_{max}^3}{3k_2 q_m}\,\frac{1-3k+3k^2}{1-k}$$

where, $k = k_2/(k_1+k_2)$, $k_1 = A_I E_I$, $k_2 = A_{II}E_{II}$.

Other types of members were also investigated, and the results almost the same.

The important point of these results is that the dissipation energy W is proportional or approximately proportional to the cubic power of the maximum external force. Since the maximum deflection is proportional to the mamimum external force in elastic structures the energy dissipation is proportional to the cubic power of the maximum deflection. Total energy, strain and kinetic energy, stored in the vibrating structure is proportional to the square of the maximum deflection. Damping capacity and damping constant are, therefore, proportional to maximum deflection and do not maintain a constant value during vibration in this case.

4. Experimental Studies

Experimental studies were done to investigate damping constant deflection relation in structures with joints using simple models. The models used in these studies are cantilever beams with bolted connections. The model without joint is also used for reference. Normal pressure in contact of the friction joints was controlled by means of torque value of the bolts. The joints in the models are located in various position.

Fig. 4 shows amplitude decay curves for the beam with bolted joint, T = 1000 kg-cm, (a) and for the beam without joint (b). Fig. 5 shows the variation of damping constants due to the position of joints. Four different types of beams are conpared in the figure. Damping constants for type D is almost the sum of those of type B and type C.

Fig. 6 shows the effects of normal pressure of the joints. The normal pressure is approximately proportional to the torque value shown in the figure. The result is well coincide with theoretical investigation.

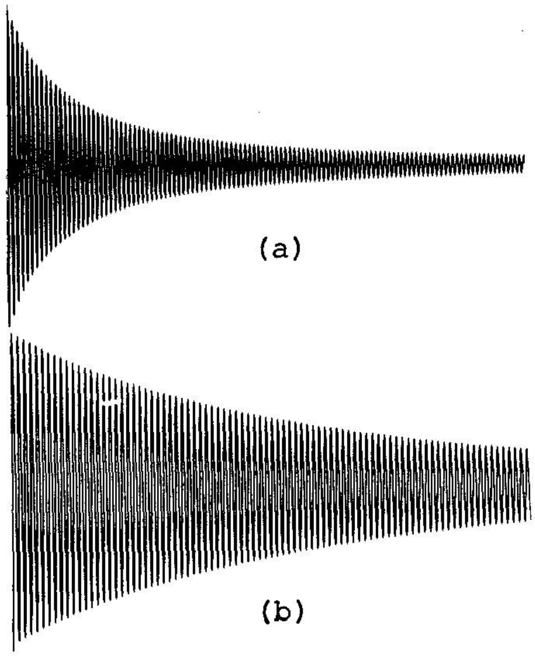

Fig. 4

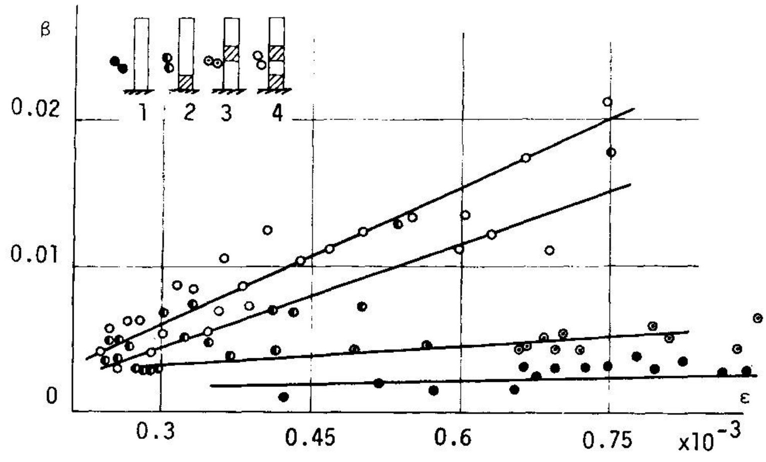

Fig. 5

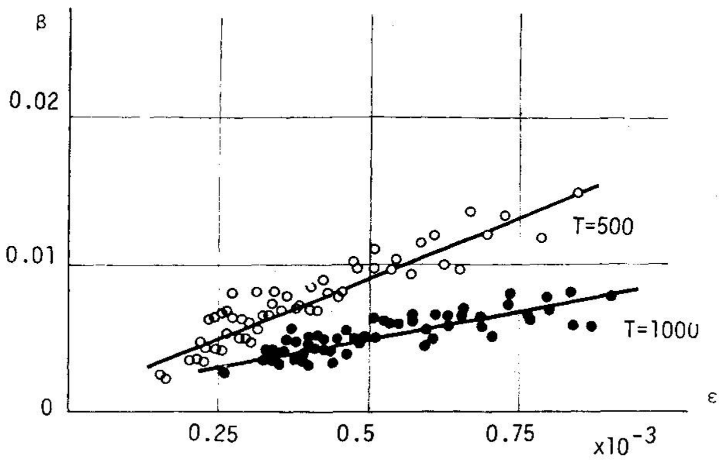

Fig. 6

5. Damping of Illustrative Model Beams

Dissipation energy from the beam with splice joints as shown in Fig. 7 during one cycle of vibration is given as follows.

$$\Delta W = \frac{8}{EI}\left[\frac{2\lambda^2 M_{omax}^3}{3(1+\lambda)^2 q_m h} + q_m h\left\{ \frac{2(1+\lambda) q_m h e^3}{3} - e^2 M_{omax} - \frac{2(1+\lambda) q_m h e + M_{omax}}{3}\left(e - \frac{M_{omax}}{(1+\lambda) q_m h}\right)^2 \right\}\right]$$

where, $\lambda = 2I/(Ah^2)$

Assuming the numerical values l = 10 m, e = 500 mm, h = 1000 mm, t = 20 mm, I = 56×10^4 cm^4, q_m = 3600 kg/cm, and E = 2.1 $\times10$ kg/cm^2, and the mode shape for the n-th order vibration as

$$\eta = \eta_o \sin \frac{n\pi x}{l}$$

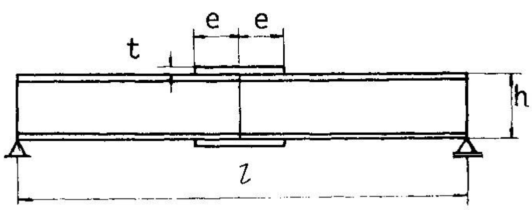

Fig. 7

the damping constant is given, approximately, as a straight line (a) in Fig. 8. If the beam has two splice joints at $l/3$ and $2l/3$ sections the damping constant is given as a straight line (b) in Fig. 8.

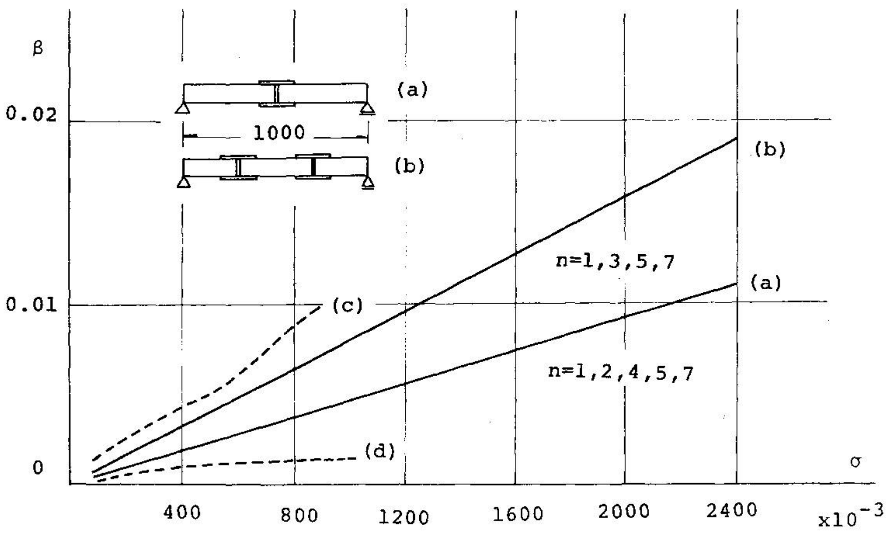

Fig. 8

Lines (c) and (d) in Fig. 8 are the experimental results obtained by U. S. Bureau of Public Roads(4) for the truss type structure with bolted joints (Line (c)) and the solid beam without joint (Line (d)). Both models have approximately 10 m span length.

6. Conclusion

Properties of vibration damping due to the friction at joints of steel structures were investigated by theoretical and experimental means. Damping constant due to joint friction increases with vibration amplitude. This effect must be considered in the dynamic analysis and design of steel structures.

References

(1) Yamada, Y., On the vibrational Damping of Structural Steel Beams, Memoirs of the Faculty of Eng., Kyoto Univ., Vol. 19, No. 1, 1957

(2) Pian, T. H. H., Structural Damping of a Simple Built-up Beam with Riveted Joints in Bending, Jour. of Appl. Mech., Vol. 24, No. 1, 1957

(3) Goodman, L. E. & J. H. Klumpp, Analysis of Slip Damping with Reference to Turbine Blade Vibration, Jour. of Appl. Mech., Vol. 23, 1956

(4) Teller L. W., & E. G. Wiles, Tests of Structural Damping, Public Roads, Vol. 27, No. 10, 1953

SUMMARY

Structural damping due to friction at the connections of steel structures were investigated by theoretical and experimental means. Non-linear properties of damping were obtained even within the elastic limit of the material. Practical application of the results to actual simple structures was discussed.

RESUME

L'amortissement structural dû à la friction des connexions de structures en acier a été examiné par voie théorique et expérimentale. Des phénomènes non-linéaires d'amortissement ont été obtenus même entre la limite d'élasticité du matériau. On a discuté l'application pratique des résultats sur le cas de structures simples.

ZUSAMMENFASSUNG

Strukturelle Dämpfung infolge Reibung an den Verbindungen von Stahlbauten wurden theoretisch und experimentell untersucht. Nichtlineare Dämpfungserscheinungen wurden selbst innerhalb der Elastizitätsgrenze des Materials beobachtet. Es wurde die praktische Anwendung der Ergebnisse auf einfache Bauwerke diskutiert.