Models and mechanisms of dissipation in bolted joints

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Preface

The research presented in this licentiate thesis is the result of a collaboration project between Scania CV AB and the Department of Solid Mechanics at the Royal Institute of Technology (KTH). Most of the actual research has been carried out at Scania’s Technical Centre in Södertälje. The project was started in December 2004 and is planned to continue to December 2008. Approximately half of the funding of this project has been provided by Vinnova and the other half by Scania - the contributions of both these organizations are gratefully acknowledged.

I wish here to express my sincere gratitude toward Professor Mårten Olsson who has supervised my work, for his skilful guidance, patient reviewing and insightful comments. I also want to thank the members of the steering committee of the project Prof. Peter Gudmundson, Dr. Boris Thorvald, Staffan Berglund, Joakim Örbom, and Ola Henriksson for their valuable input on the general direction of the work.

Finally I want to thank my colleagues and co-workers at Scania and at the Department of Solid Mechanics - there are many of you who have helped me, encouraged me, and made these years more stimulating.

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Introduction and motivation

The behaviour of frictional joints is non-linear mainly due to friction in the contact interfaces and the possibility of shatter. Structures assembled with frictional joints inherit these non-linearities, and when such structures are subjected to dynamic forces both the joints’ contribution to damping and the non-linear stiffness will influence the dynamic response.

The automotive industry has a strong desire to predict the dynamic response of structures for strength and durability assessments. Ideally this prediction is be made before physical prototypes are manufactured, at a stage when the structure only exists as a drawing. Trucks and their subsystems are to a large extent assembled with frictional joints and subjected to a multitude of dynamic forces. A key challenge in simulation exercises of such joined structures is to model the mechanical joints adequately.

Consequently the aim of this project is to provide modelling techniques for frictional joints appropriate for dynamic simulation of assembled structures. In the present thesis it is primarily the quasi-static energy dissipative characteristics of frictional joints that are investigated, both analytically, experimentally and by means of the finite element method. Future work will aim at linking the quasi-static properties of joints to the dynamic properties of vehicle systems.

Bolted joints need to be designed such that large global sliding does not occur. If the relative displacement between two members of a joint becomes too large the bolt comes into contact with the joined members, which quickly results in failure of either the bolt or one of the members. When a bolted joint is subjected to tangential forces there are two principal restraints of sliding; firstly, the frictional forces due to pretension and friction, and secondly, bending of the bolt. As the tangential forces, transferred via friction over the joint, increases, a slip zone develops in the contact area, Figure 1. At a sufficiently large tangential force the joint slips over the entire contact interface. The integrated slip results in a relative displacement of the members, in this way introducing bending of the bolt. Thus, even when the tangential forces do overcome the sum of available frictional forces the joint still provides some stiffness, although there is obviously a risk of failure of the bolt.

![Figure 1. Schematic illustration of a tangentially loaded joint, stick- and slip-zones indicated.](image-url)
In engineering structures the contact length between the joint members is in the order of $10^{-2}$ m. With an allowable strain in the order of per mille the relative displacement $u_{rel}$ in the micro-slip region is in the order of $10^{-3}$ m. Although the relative displacement is small the micro-slip’s contribution to the system damping is significant.

If one considers that the inertia forces in a vibrating beam $F = ma$ via some geometrical leverage ratio $r = L_1/L_2$ are transferred via friction, such that the transferred forces $F_i = rF$, refer to Figure 2.

![Figure 2. Schematics of a cantilever beam with bolted joint.](image)

Then the total dissipation during a cycle of vibration is $\Delta W = 4F_t u_{rel}$. Assuming that the system vibrates at the resonance frequency with the amplitude $u_{amp}$ permits formulating the equivalent viscous damping as

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\zeta = \frac{\Delta W}{4\pi T_{max}} = \frac{4ru_{rel}^2ma}{2.\pi m v^2} = \frac{2ru_{rel}^2}{m u_{amp}^2}
$$

which, for typical engineering structures with $u_{amp}$ in the order of $10^{-2}$ m and $r$ in the order of 10, is in the order of some per cent. This contribution is significantly larger than the contribution from material damping and in line with measurements on assembled structures. The equivalent viscous damping will be larger for systems with several larger joints or joints in global sliding and lower for systems with fewer and stiffer joints. Note that because the relative displacement is a non-linear function of the ratio between transferred forces and available frictional forces, the equivalent viscous damping generally varies with the amplitude of motion.

Modelling as close to “the real physics” as possible of mechanical joints is challenging for several reasons. The difference in scale between a truck and the relative displacement in the joints is one complicating factor. Also the numerically challenging task of detecting contact closure and the onset of friction makes computational times prohibitive even for smaller subsystems. Both these obstacles are especially problematic in fully dynamic analyses where inertia forces in the joint are also taken into account. In dynamic analysis of large structures it is therefore imperative to use grossly simplified models of the joints. It will remain a useful simplification also in the future, when computational methods and resources have improved.
However, if inertia forces in the joints are neglected it is feasible to simulate micro-slip by means of the finite element method. This allows computing stiffness and dissipation for the joint in statics and may be serviceable for parameter estimation of a simplified dynamic model.

When the qualitative analysis presented above is extended in some detail, it becomes apparent that the form with which the contact pressure is distributed over the contact length is an important factor for determining the relative displacements and hence the damping. The total clamping force is rarely evenly distributed over the joint’s contact area but varies much, generally to be largest closest to the bolts. For joints with multiple bolts the pressure distribution is a more or less conscious choice but in other cases it is not so. Non-planar pressed sheet metal is one example.

In **Paper A** the influence of the distribution of pressure is demonstrated analytically and experimentally. It is proven that for an idealized joint there exists a pressure distribution that maximizes the relative displacement, and the shape of that distribution is quite simple. **Paper A** also includes experiments and finite element simulations of a very simple frictional joint with two different pressure distributions. The most important conclusions from that study is; i) The pressure distribution may alter the frictional dissipation. ii) Finite element simulations of micro-slip in plane contact surfaces may be used as a predictive tool. iii) Future investigations need to be made into the predictive capabilities of simulations, in particular for surfaces with discontinuities. In **paper A** the only dissipative mechanism taken into account is the Coulomb friction and the materials of the contacting bodies are considered linear elastic or rigid. A bi-product of this study is a patent covering some methods of adapting the contact pressure distribution in joints for maximizing the damping (Pat. no. SE 528 765 C2).

**Paper B** is a largely experimental research effort where a simple structure, well represented by Figure 2, is studied in statics as well as in dynamics. It is shown how the static force-displacement characteristics may be used for identifying parameters of a simplified joint model that later is used for dynamic simulation. In addition the idea of modifying the properties of the joint by the introduction of thin metallic inserts between the contacting bodies is presented. These inserts are so thin (0.2 mm) that they do only mildly change the initial stiffness of the joint but their presence does alter the distribution of the clamping pressure significantly. Data from quasi-static testing of the joint with sixteen geometrically distinctly different inserts generating sixteen different pressure distributions is presented in this paper. It is shown how different inserts generate different dissipative characteristics of the joint. Furthermore it is demonstrated by experiments how the assembled structure inherit these different characteristics showing that it is possible by means of a thin insert to alter the dynamic properties to generate larger or smaller dynamic response.

In **Paper C** the experimental results of **Paper B** are clarified. A series of finite element simulations give further evidence for that simulations may be used for prediction of joint mechanics in relevant engineering structures. The excessively large difference in dissipation between the inserts in **Paper B** is shown to arise from cyclic plastic deformation in the vicinity of surface discontinuities. More precisely, the dissipation is due to the motion of the material back and forth over the contact edges and this mechanism is given the name “sliding-over-edge”. **Paper C** also
demonstrates how the finite element method may be used to understand complex joint mechanics and may possibly also be used to predict run-in effect of decreased clamping force observed in practically all joints.

Together these papers give a view that finite element simulations of relevant engineering joints may be used for prediction of static experiments. Naturally a rather precise knowledge of materials, clamping force and the coefficient of friction is required but it remains feasible. Furthermore these papers provide a detailed explanation of how the clamping force and the distribution of pressure in the joint affects dissipation. Finally an initial successful attempt to use simplified models trimmed to static measurements has been demonstrated.

Future work

Concluding that the finite element method may be used for prediction of joint behaviour in statics the natural continuation of the work is to provide tools for dynamic simulation. This will allow for considerable improvements in the workflow of the product development in the industry. In particular accurate estimation of dynamic system properties allow for early estimates of dynamic fatigue loads. Not only is this expected to improve designs overall but it will also allow for a more accurate comparison of load severity on different markets and segments. Finally, it is expected that the gained understanding of joint mechanics will contribute directly in joint design with focus on robustness and with the possibility to design for damping. Therefore, the continuation of the project will emphasize the development of models and tools for dynamic simulation of joined structures.

List of appended papers

The following papers are appended to the thesis.

