CONTACT PROBLEMS IN MECHANICAL JOINTS

by

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ABSTRACT

The opening of prestressed bolted joints under harmonic loading is studied. The problem is motivated by the bolted joint between the lower end and main body of an automobile engine connecting rod. This is a preliminary report of a student project currently underway.

Notation

C	Constant
E	Young's Modulus
L	height of block
u,v,w	displacements in x, y, and z directions respectively
w_R	z displacement of top node of ROD element
w_1, w_2, w_3, w_4	displacement in z direction of the four grid points that points that lie on the top surface of the block
σ_{ii}	stress
σ_{zz}	computed normal stress amplitude at surface grid points from a SOL 26 run
σ_o	magnitude of the clamping pressure supplied by the bolt
σ_1	amplitude of applied dynamic stress
ν	Poisson's ratio
ρ	mass density of block material
ω	frequency of dynamic load (rad/s)

INTRODUCTION

When beginning to study the physical behavior of a complex mechanical system such as a connecting rod/bolt joint, one sometimes looks at very simple models that display some of the characteristics of the real system. As the underlying physics of these simple systems is learned, more sophisticated modeling techniques can be applied. In this way, the most restrictive assumptions can be removed.

In this spirit the current research began with a fundamental assumption: the joint has a plane of symmetry with respect to geometry, material, and loads. The deformation of the material is assumed to be small, at least up to the point of initial gap opening. Finally, the loading is assumed to be fully reversed. With these assumptions, the finite element method seems to be an ideal analysis method to use. MSC/NASTRAN, Version 64A, was used to perform the FEA.

BLOCK

As a starting point a very simple one-dimensional joint between an elastic block and a rigid plane was analyzed throughly (Fig. 1). The block models 1/2 of the connecting rod bolt and surrounding material. In the following sections the physical modeling, the construction of the finite element model, and the use of dimensional analysis will be discussed in detail.

A. Physical Modeling

The block rests on a rigid frictionless surface. It is made of a homogeneous, isotropic material which is linearly elastic. On the top surface of the block a uniformly distributed static pressure is applied. In addition, a sinusoidally varying, uniformly distributed dynamic pressure is applied to this surface. The sides of the block are free surfaces. The rigid surface represents the joint. The static loading models the clamping pressure the bolt applies to the surrounding connecting rod material. Notice that the assumption of a uniformly distributed static load is not realistic. The dynamic loading represents the dynamic forces the rest of the connecting rod imparts as it accelerates through a complete piston cycle. The contact surface was assumed to be perfectly flat with no curvature near the edges.

B. Finite Element Modeling

The finite element model consisted of 44 grid points connected together by 10 eight-noded HEXA solid elements (Fig. 2). Since the HEXA is an elasticity element, D0Fs 456 were constrained for all grid points. The grid points resting on the rigid surface were constrained from moving in the z-direction. This was done to determine when loss of contact occurred. From elementary contact theory it is known that two bodies lose contact when the normal stress at the interface becomes tensile. By requesting the normal stresses in the z-direction for the surface grid points it was possible to determine when separation began. If 20-noded HEXAs were used, it would have been difficult to ascertain this because a discretized uniform inward surface pressure produces both compressive and tensile nodal forces for these elements.

Before beginning a frequency response analysis (SOL 26) one must be concerned about exciting only the axial modes of vibration and avoiding any "cantilever-type" modes. To achieve this, we applied a set of single point constraint equations (SPC) and a set of multipoint constraint equations (MPCs) to the structure that effectively created a ROD-like element with cross sectional "breathing" (Fig. 3). This modeling essentially captured Poisson's ratio effects. Notice the coordinate system used to specify grid point displacements. This particular coordinate system made the MSC/NASTRAN data preparation very simple.

As mentioned above, a frequency response analysis was performed on the structure. However, the physical modeling left a static pressure in addition to the harmonic loading acting on the structure and in frequency response analysis *all* the applied loads are sinusoidal. Fortunately the problem is completely linear and the principle of superposition can be used. The static problem was solved easily since the structure is statically determinant. The internal normal stress in the z-direction was just the applied stress, thus ensuring equilibrium. Therefore, to determine whether the block will lose contact or not add this static stress to the computed dynamic stress acquired from a SOL 26 run.

The rigid body modes were removed through the MPC equations and the z constraint at the bottom of the block. The MPCs allow only symmetric "breathing" and does not allow a rigid body translation in the x or y direction or a rigid body rotation about the z axis. The clamping prevents rigid body translation in the z-direction and rotation about the x and y axes.

C. Dimensional Analysis

When studying the behavior of a mechanical system, it is hard to determine what parameters to vary and how to present the results. Each FE run can be viewed as a numerical structural mechanics experiment. By using dimensional analysis the most information can be obtained from the fewest runs. In our work the most important parameter was the amplitude of the normal stress at the surface, σ_{zz}, computed from a frequency response analysis. It depends on many variables. They can be placed in three general groups: material properties, structural geometry, and loading parameters. Using the Buckingham Pi theorem, these variables can be grouped together in dimensionless ratios. We found that σ_{zz}/σ_o is a function of v, σ_1/σ_o, and $\Omega = \omega/((C/L)^*\sqrt{E/\rho})$. Therefore liftoff occurs when σ_{zz}/σ_o equals one, because then the *total* normal stress at the surface ($\sigma_{zz} + \sigma_o$) reaches zero. The σ_1/σ_2 at which this occured was denoted as $(\sigma_1/\sigma_o)_{cr}$. We scaled Ω so that at the fundamental frequency of the structure Ω would equal 1. C was found to be approximately $\pi/2$.

A single plot of $(\sigma_1/\sigma_o)_{cr}$ versus Ω was considered the most effective way to present the data (Fig. 4). Along this curve σ_{zz}/σ_o equals one. Above this curve the loading conditions would produce dynamic instability where the block would begin bouncing on the rigid surface. Below the curve, contact would be maintained. Generation of Figure 4 actually requires only one frequency response finite element run. For each frequency, the response can be scaled so as to find a critical value of prestress $(\sigma_1/\sigma_o)_{cr}$.

D. Results

The block was considered to be steel with the following material properties:

$$E = 2.068e5 \text{ MPa}$$
$$v = 0.30$$
$$\rho = 7.83E\text{-}9 \text{ Mg/mm}^3$$

The yield stress for this steel was found to be approximately 1380 MPa. Assume the prestress σ_o equals 460 MPa (the specific value is not important here). Using SOL 3, one finds the fundamental frequency to be slightly over 64,000 Hz. Next SOL 26 was used to generate the raw data. Figure 4 shows the end result. Notice that as Ω approaches zero, $(\sigma_1/\sigma_o)_{cr}$ approaches unity. This is to be expected because the loading becomes completely static. As Ω approaches $\Omega_{natural}$, $(\sigma_1/\sigma_o)_{cr}$ approaches zero. With no damping, the amplitude of the response of the structure increases without bound as one nears the fundamental frequency.

BLOCK/ROD STRUCTURE

To improve the "one-dimensional" modeling, one adds a ROD element to the FE model to represent the bolt (Fig. 5). To model the interaction of the bolt head with the top surface of the connecting rod material, one uses the following MPC equation : $w_R = 0.25*(w_1+w_2+w_3+w_4)$. The cross sectional area of the bolt was assumed to be 1/10 that of the block, which now represents the surrounding connecting rod material. As before, the ROD was constrained to the rigid surface to obtain normal stress output. Dimensional analysis was used again. The fundamental frequency for this new structure was essentially the same as before. Figure 6 shows the dynamic behavior of this structure. Notice that the left curve ventures above $\sigma_1/\sigma_o = 1$ because the bolt kept the block in contact for a small range of tensile stresses greater than the clamping pressure. In general terms, the addition of a bolt-like component to the structure shifts the curve upward.

CONCLUSIONS

The work to date has produced two universal curves that convey the dynamic stability characteristics of the systems analyzed. The next phase of our work will focus on improving the geometric modeling of the joint, applying the dynamic loading on the side where it actually acts, and comparing the results obtained with those of other researchers.

References

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2. Johnson, K. L., Contact Mechanics, Cambridge University Press, 1985.

3. Gockel, M. A., editor, "MSC/NASTRAN, Handbook for Dynamic Analysis, Version 63", The MacNeal-Schwendler Corporation, June 1983.

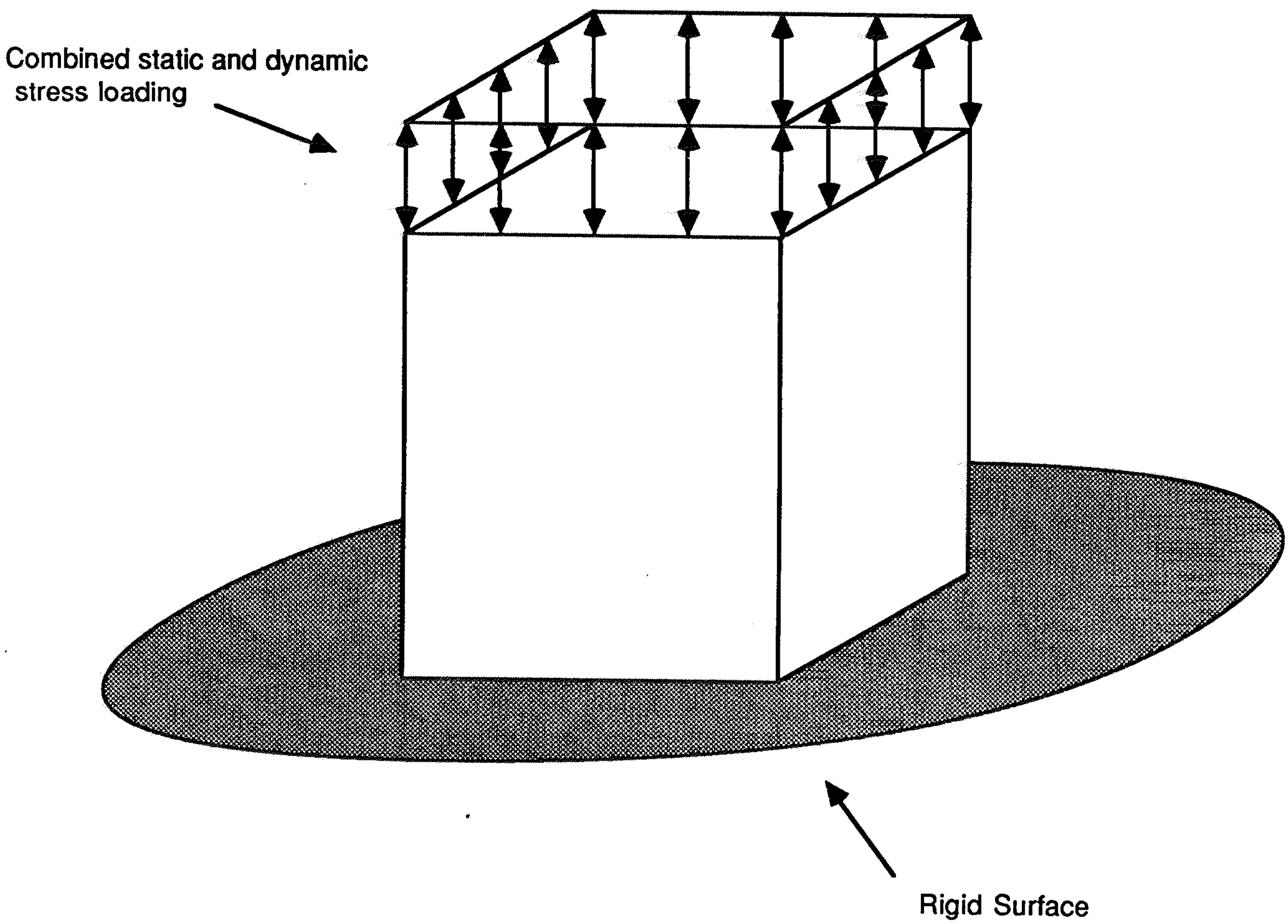


Figure 1. Block model of connecting connecting rod joint

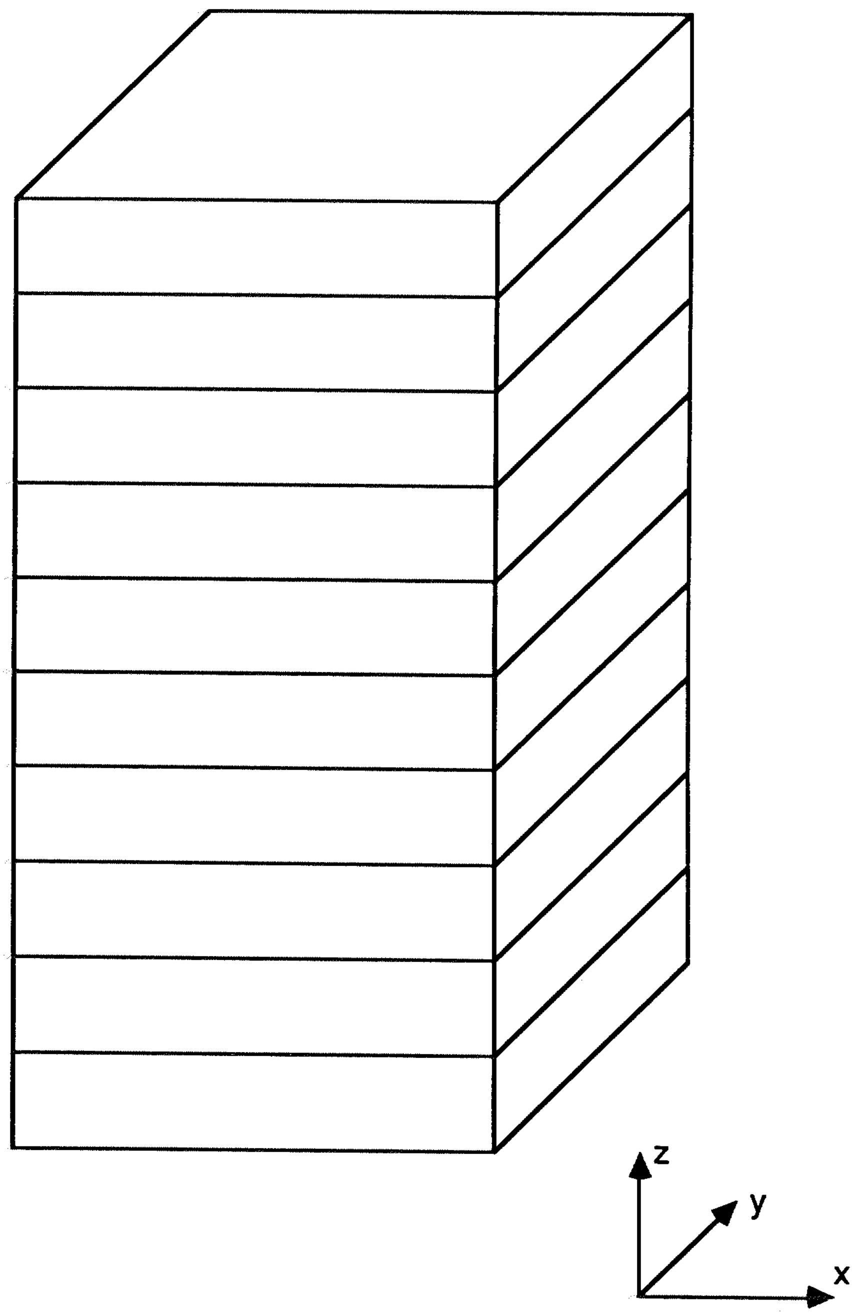
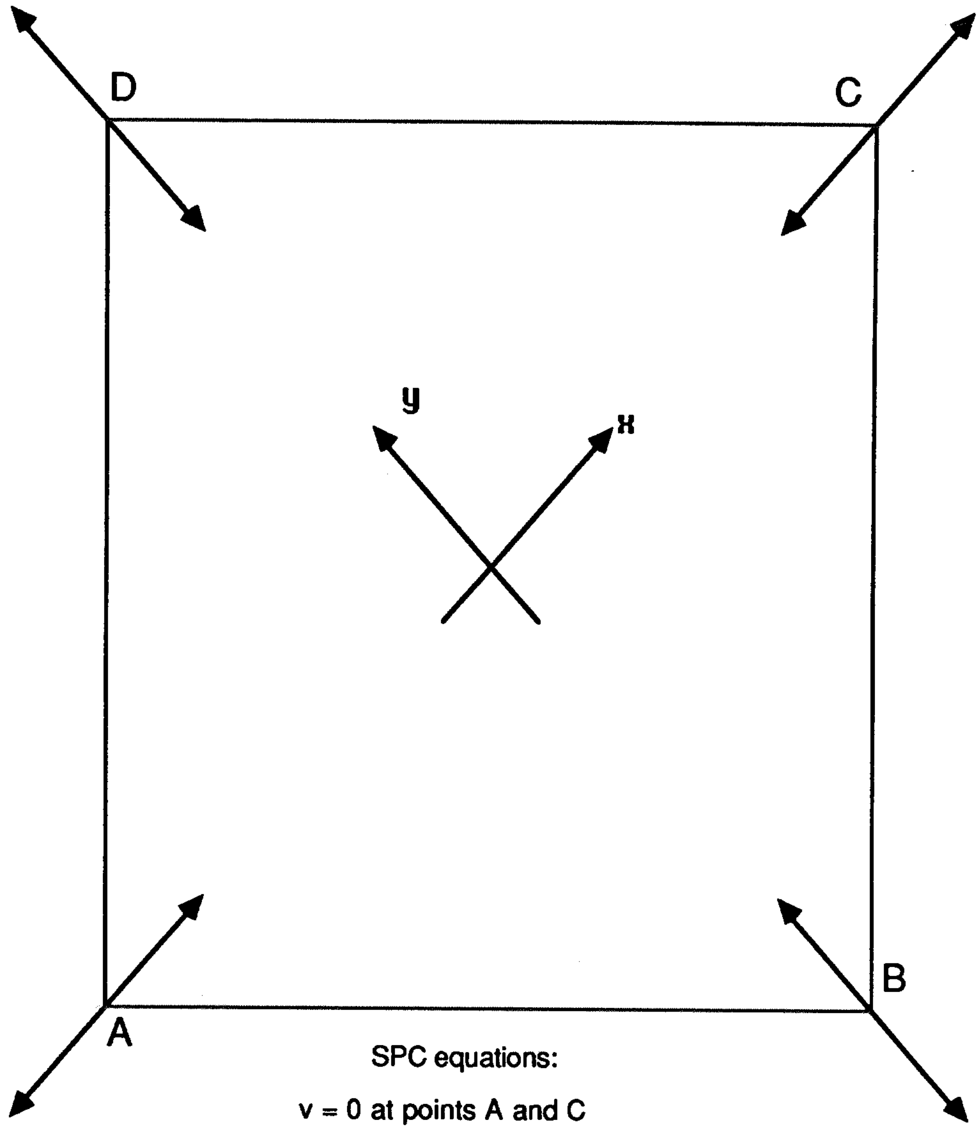


Figure 2. Finite Element Model



SPC equations:

$v = 0$ at points A and C
$u = 0$ at points B and D

MPC equations:

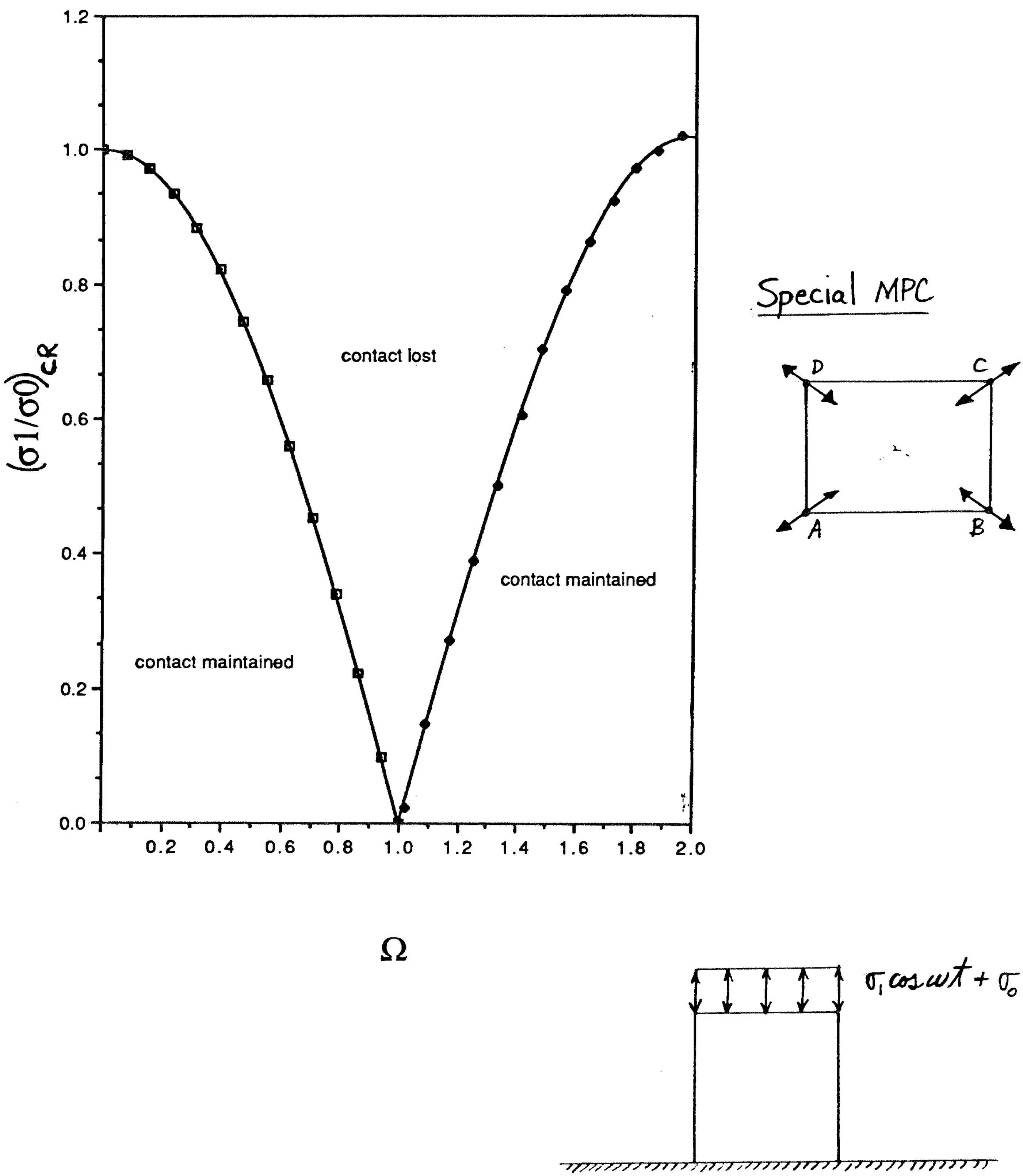
$$u_A + u_C = 0$$

$$v_B + u_C = 0$$

$$v_D - u_C = 0$$

Figure 3. Eliminating Flexural Oscillation

Figure 4: **Contact of Block under Harmonic Loading**



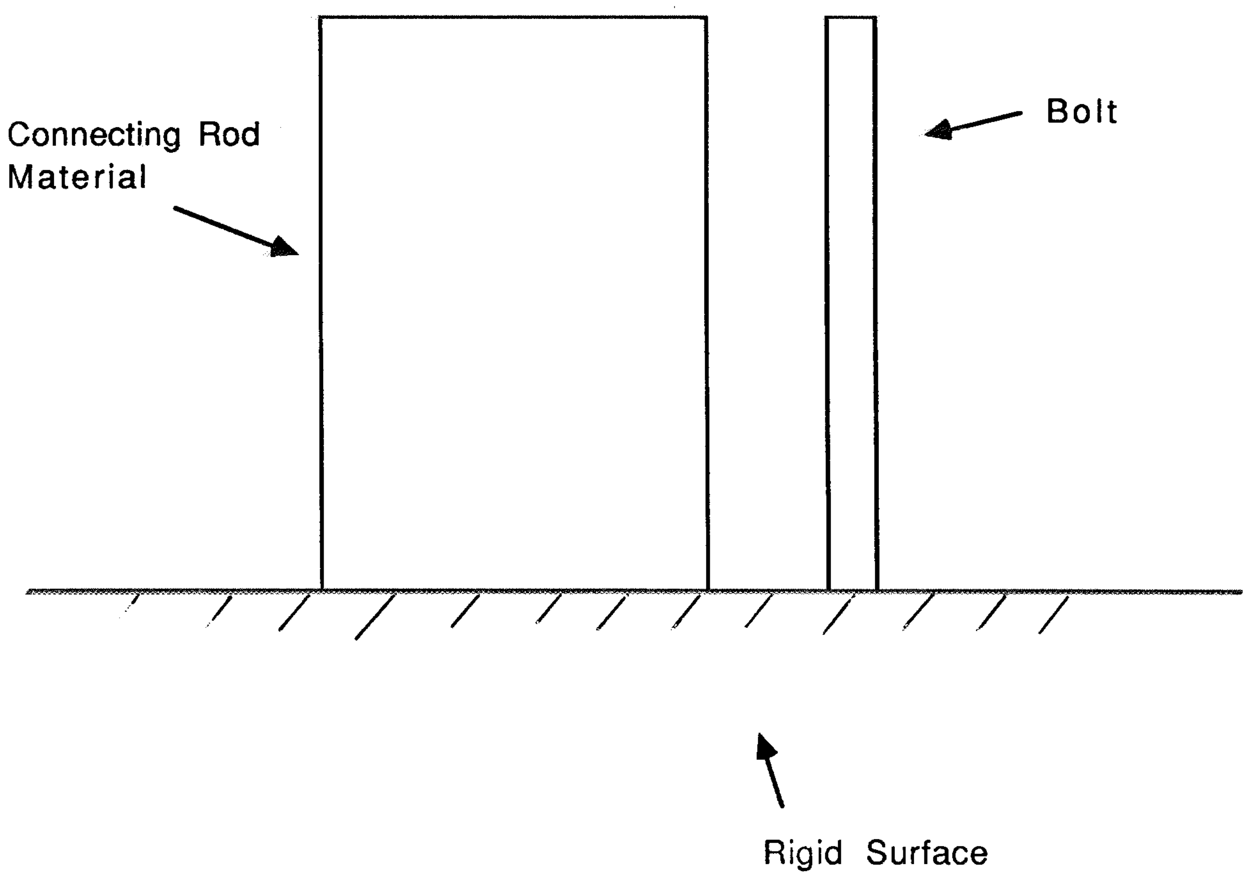
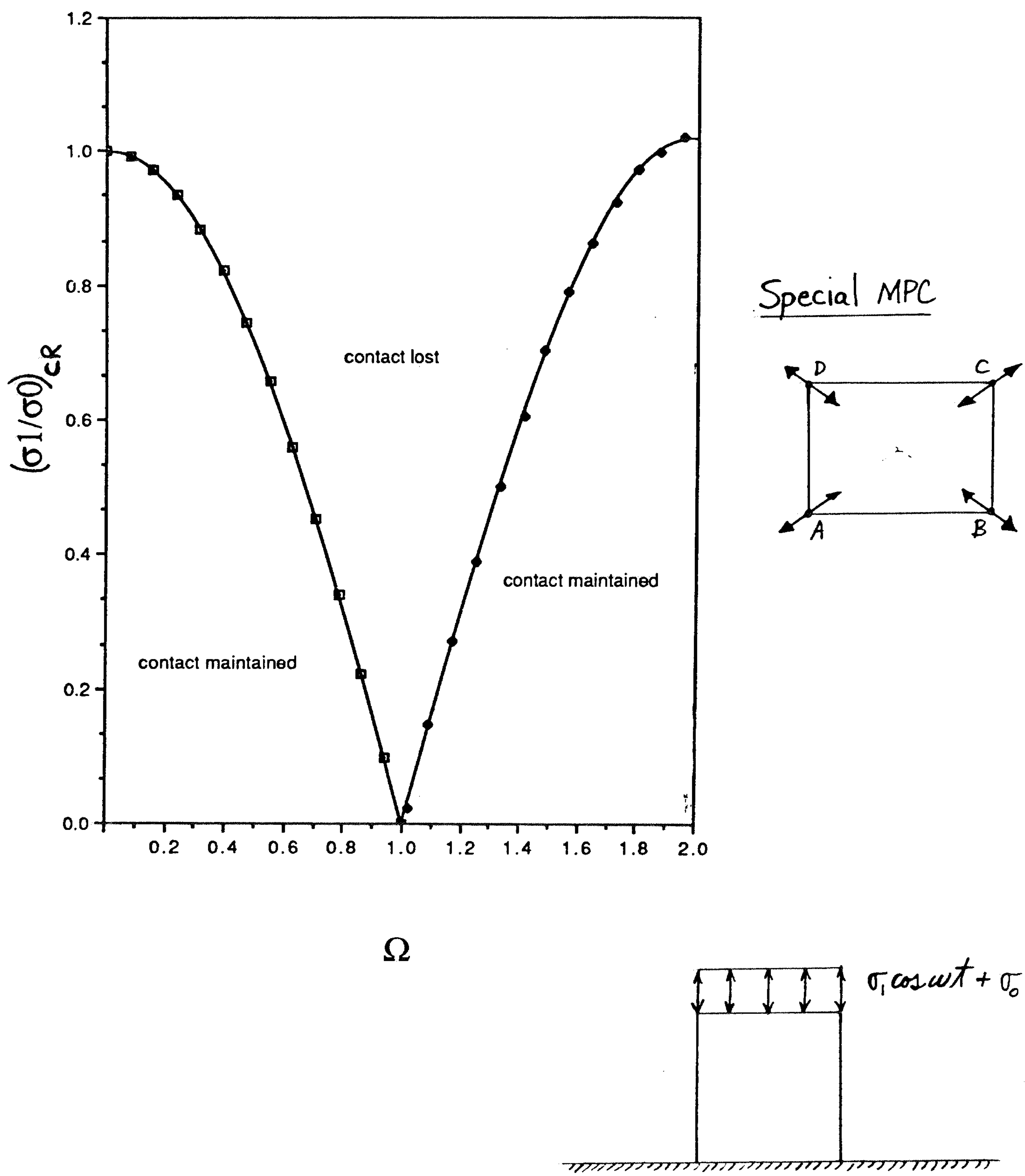


Figure 5. Improved Model of Joint

Figure 4: **Contact of Block under Harmonic Loading**



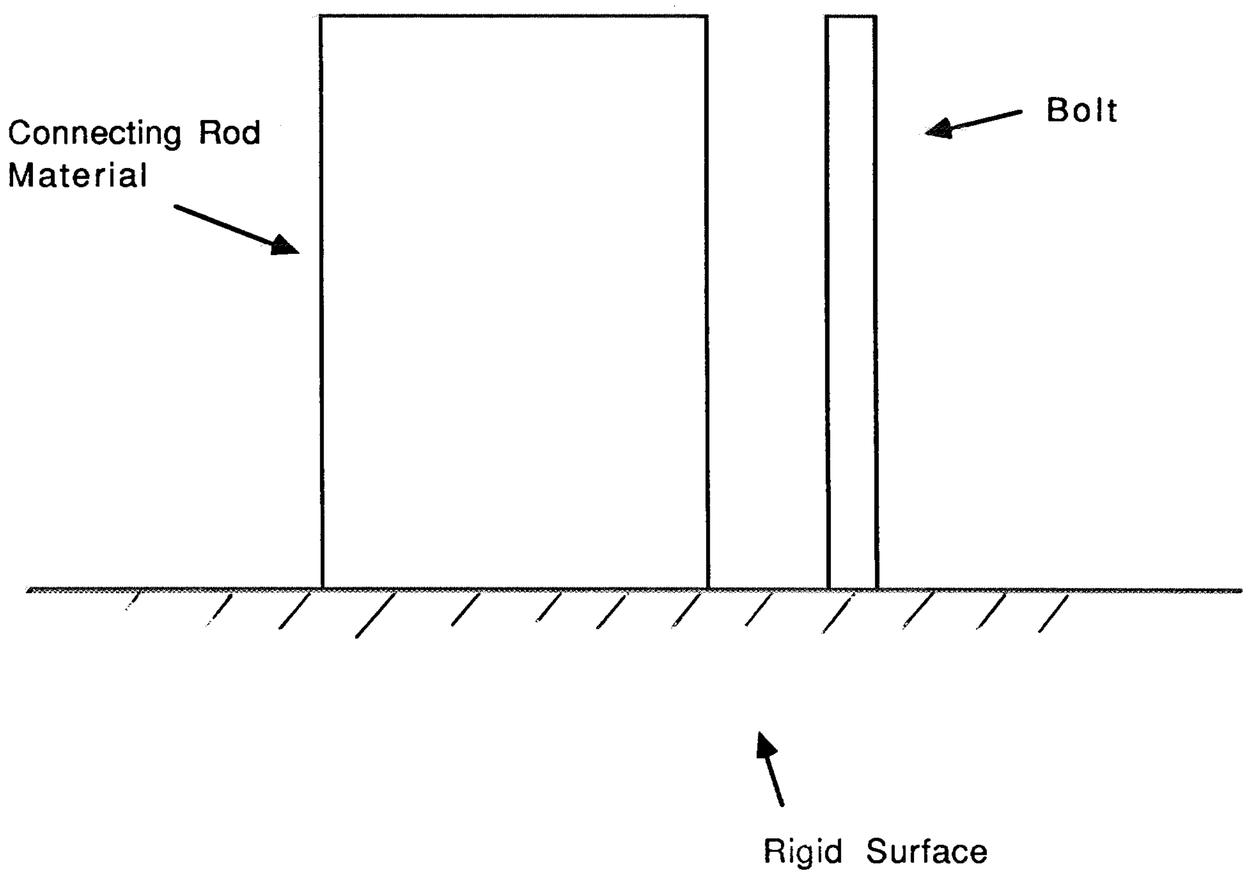


Figure 5. Improved Model of Joint

Figure 6: **Block/Rod Structure**