Collision between Two Deformable Structures

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Summary This paper summarizes the complete solution, modal solution, local models and experiments on beam-on-beam collisions. The common features of structural collisions are explored through the analysis on the collision between mass-spring systems. These features are further exhibited in more complicated ring-on-beam collisions, based on the solutions obtained by the proposed MS-FD model.

INTRODUCTION

Over the last 50 years, the studies on dynamic plasticity of structures mainly concerned a single structure's response to prescribed impulsive/pulse loading or to the impact of a rigid projectile. However, the collision between two deformable structures (CBTDS) is a much more common incident in various engineering scenarios and is of practical interest. Hence, aiming to extend our knowledge to these more realistic problems and reveal some fundamental features of CBTDS, our group at HKUST has conducted a series of studies since 1998. A particular attention was paid to the energy partitioning between two colliding structures which actually reveals the structure's ability to absorb energy in a collision event and is exceptionally important for developing safety devices.

COMPLETE AND MODAL SOLUTIONS

The first compete solution of CBTDS was obtained by Yu *et al* [1,2] who analyzed a flying free-free beam impinging onto a cantilever beam. This solution considered the local rigid-plastic shear sliding, which actually defines a local rigid-plastic contact spring, as will be discussed later. After a shear-sliding phase, the stick assumption, which assumed the contact points remain attached to each other, was employed, so that the two-beam system was treated as a single T-shaped beam in the subsequent global flexural deformation.
The complete solution has to handle various combinations of various phases of the two beams. This complicity motivated us to examine simplified approaches, e.g. the modal approximation technique. However, difficulty was found in selecting an appropriate rigid, perfectly plastic mode based on the Lee's principal, since the latter always results in a fundamental mode, i.e. that with a single hinge in one of the colliding beams. As a new powerful tool, an elastic, perfectly plastic (E-PP) mode technique was proposed in Ref. [3], in which a potential plastic hinge is replaced by a natural hinge with an elastic-plastic rotational spring. In other words, the E-PP solution allows the structures to naturally select a proper mode. The E-PP modal solution was demonstrated to provide a good approximation to complete solutions, as shown in Fig. 1, which demonstrates the effect of beam thickness ratio on the energy partitioning between beams.

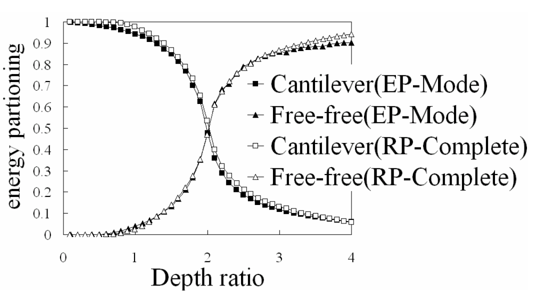

Fig. 1 Energy partitioning between two beams

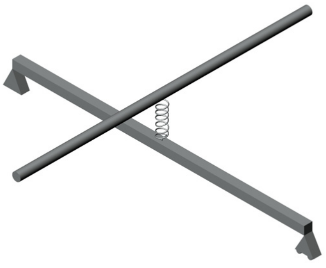
Fig. 2 Beam-on-beam collision with a local contact spring

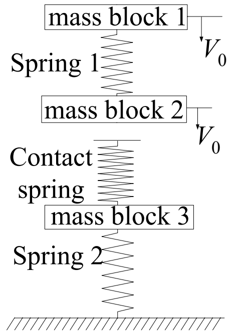

Fig. 3 A simple mass-spring collision system

LOCAL CONTACT MODEL

The local contact model between the two colliding structures is a vital issue in the structural collision, because it theoretically defines the interaction between the two colliding structures and provides a solution for the transmission of momentum and kinetic energy from the flying structure to the target one. Since the contact area is usually very small compared with the dimensions of the structures, the inertia of the locally deformed regions is negligible in the dynamic analysis, thus its behavior can be modeled by a massless non-linear contact spring. Thus, for a typical collision between a free-free cylindrical beam and a simply supported rectangular beam, the simplified model can be sketched as shown in Fig. 2. Due to the initial velocity discontinuity at the contact points (e.g. the mid points of a flying free-free beam and a target simply-supported beam), the relative displacement of these points exists and represents the magnitude of local contact deformation. Hence, if a contact model can relate the interaction force to the contact deformation, it defines the mechanical property of a (non-linear) contact spring. On the other hand, for each colliding structure, this contact force can be treated as an external force pulse, whilst the stick assumption is no longer necessary, so that the separation

between the colliding beams and multi-collision phenomena can be observed.
Several local contact models for beam-on-beam collisions have been proposed by Ruan and Yu [4]. Owing to the complexity of elastic-plastic contact problem, each contact model proposed in Ref. [4] assumes a particular deformation pattern and neglects some factors. For instance, the Elastic-Plastic (or Rigid-Plastic) Shear Deformation (EPS/RPS) model only accounts for the shear deformation in the contact region; the Blunt Indentation (BI) model assumes hydrostatic pressure applied to the material under the contact region and the deformation possesses radial symmetry; while the Uniaxial Compression (UC) model assumes a uniaxial compression along the direction of indentation and neglects the material's Poisson's effect and shear deformation.

ANALYSIS OF A MASS-SPRING SYSTEM

In order to reveal the fundamental features of structural impact/collisions with reduced complexity, one may utilize simple mass-spring systems, in which the complicated geometric analysis is no longer required whilst the two most essential factors for the structural dynamics – inertia and stiffness – are incorporated. A simple mass-spring colliding system (shown in Fig. 3) proposed in Ref. [5] was found equivalent to the E-PP modal solution of beam-on-beam collisions. Thus, the study of this mass-spring model is able to bear some physical meaning in real structures. Through this study, some common features of structural collision are elaborated. In general, a structural response to impact can be divided into two stages: a very brief collision stage, followed by a global structural deformation stage. The first stage starts with a severe velocity discontinuity in the contact region, and characterized by a local velocity change together with local contact dissipation. In the second stage, a restoring instant exists at which the stronger structure transfers from an energy dissipation state to a non-dissipation state, and the total energy dissipated by this structure is termed the restoring energy. The remaining kinetic energy after this restoring instant will be completely dissipated by the weaker structure, if the latter exhibits no deformation-hardening. For the structure with constant load-carrying capacity during its large plastic deformation, the initial velocity will not affect the energy partitioning; while the increase of the relative mass of the impinging structure will make the energy-partitioning pattern approaching an elementary static estimate; that is, the structure with lower strength will dissipate all the input energy. These features are further exhibited in a more complicated ring-on-beam collision based on the solutions obtained by the proposed MS-FD model [6].

EXPERIMENTS

In order to verify the above theoretical models, dynamic experiments were conducted on beam-on-beam collisions. The flying free-free beam was accelerated by a bullet fired from an air gun. In order to avoid a direct impact of the bullet onto the free-free beam before the beam-on-beam collision of the prime interest, an aluminum medial was employed to transform a part of kinetic energy from the bullet to the flying beam. The velocity that the free-free beam thus gained was up to 20m/s, which then generated notable plastic deformation in the two colliding beams. The flexural profiles of the beams after collision were scanned and fitted by piece-wise linear curves, which was then used to calculate the energy dissipated by each beam in its global flexural deformation. It is found that most of the curvature change was concentrated in the middle portions of the two beams, indicating that the most of plastic deformation occurred in their mid-spans. This fact verifies the modal solution which assumes that merely a single plastic hinge forms in each of the colliding beams at its mid-span while the two halves of the beam rotate about this hinge as rigid bodies. The energy dissipation ratio of the two beams obtained from the experimental results shows a good agreement with the theoretical predictions, verifying the theoretical models previously developed.

CONCLUSION

Our study indicates that the previous theoretical approaches for single structure's dynamic response are still applicable on the collision between two deformable structures. However, the local contact force-deformation behavior (e.g. as a massless contact spring) should be incorporated into the model to relate two structures' response. The E-PP modal solution technique was proposed as a powerful technique to replace the R-PP modal solution. In respect of energy partitioning, it was shown that the weaker structure always dissipates more energy. The energy-partitioning pattern mainly depends on the structures' mass and stiffness, rather than on the magnitude of initial velocity, especially when the structures display no deformation-hardening.

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References

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