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Composite wall test-chamber assessment for hydrogen blast loads

Ram Kumar Singh

Department of Mechanical and Industrial Engineering, Indian Institute of Technology-Roorkee, Roorkee 247667, India

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ABSTRACT

Simplified energy based analytical models and close form solutions are used to evaluate the limiting quasi-static and impulsive over-pressure transient response of a composite wall test-chamber, which is validated and confirmed with experimental observations using controlled hydrogen combustion tests. Further a detail three-dimensional transient finite element simulation is presented to compare the test results with the numerical results. The effectiveness of evolved procedures is highlighted in the context of the blast resistance evaluation of experimental facilities besides the other important infrastructures that might be subjected to hydrogen blast loads. Despite the known limitations of the simplified analytical models and close form solutions, its usefulness is emphasized to develop fundamental understanding for arriving at sound engineering judgment for conducting blast experiments in a safe manner. With this background, the interpretation of the associated detail three-dimensional transient dynamic finite element analysis results is shown to be consistent and in good agreement with the test observations.

1. Introduction

For the prospective upcoming hydrogen economy; it will be important to carry out the safety assessment with regard to distribution and combustion of hydrogen within equipment and structural enclosures which could result into flame acceleration induced deflagration or detonation blast under the accidental conditions. This would require transient dynamic analysis of blast resistant structures and in-depth structural safety research for nuclear, aerospace, chemical process and transportation sectors. It is desirable to preclude hydrogen explosion with suitable design measures and mitigate or limit the consequences in case of its accidental occurrences. In view of the complex nature of the blast waves and the associated uncertainties, the assessment of the response data such as blast induced transient combustion gas impulsive pressure, acceleration time histories and peak displacements of the structural members for vented and confined hydrogen explosions in carefully controlled experiments are important. The insight gained from the combustion experiments within test-chambers and enclosures backed up with structural safety assessment and evaluation of its limiting impulsive and quasi-static over-pressure capacity is useful for performing blast tests in a safe and reliable manner and more importantly for the evolution of important infrastructures for hydrogen economy program.

A typical blast test-chamber facility (Fig. 1) earlier used for performing the hydrogen combustion experiments at Karlsruhe Institute of Technology (KIT), Germany consists of a composite steel wall structure with three dimensional frame and shell members [10,11,8,9]. The test-chamber structure of 8650 mm × 5530 mm × 3640 mm size is covered with corrugated steel plate of 0.8 mm thickness bolted on the inner side of the stiff frame structure and steel plate closure of 3 mm thickness bolted on the outside of the frame structure to form the outer structural barrier for the chamber enclosure. Rubber sheets are mounted in between the two plates and the frame structure for achieving requisite damping and acoustic characteristics of the test chamber. The composite structure thus formed acts as a fire wall to contain and absorb the hydrogen blast wave energies released during the explosion experiments within the test-chamber. For blast resistant structures; it is desirable to dissipate the energy over a wide range of frequencies since the deflagration and detonation induced blast waves have a very broad spectrum of frequencies and significant uncertainties do exist with regard to its frequencies. In case of confined explosions, the frequencies of excitation due to the released energy depend on the enclosure size, the location and size of the source kernel and the subsequent wave propagation speed depending on the flame acceleration, which decides whether the blast wave is in supersonic or sonic / subsonic regime. Acceptable levels of impulse induced vibration and resultant stresses are achieved for the combustion test-chamber with multiple layers of rubber sheets placed in between the frame and corrugated wall structure which significantly dissipate the wave energy. The composite wall structure construction helps to spread the structural frequencies over a wide range and thus accounts for the broad spectrum of blast wave frequencies. This is an important feature of the structural barrier design

E-mail addresses: rksinghfme@iitr.ac.in, rksingh175@rediffmail.com.

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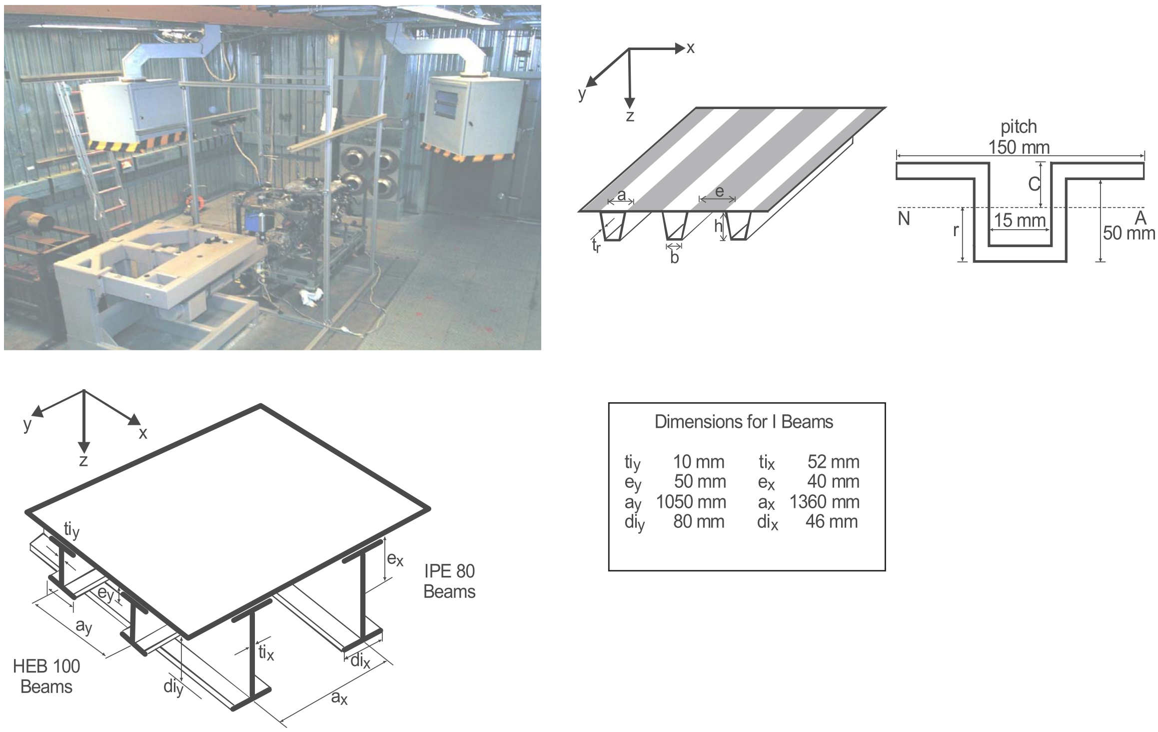

Fig. 1. Hydrogen Combustion Test -Chamber and Typical Left Wall Frame Structural Details Details with IPE 80 and HEB 100 beams and 3 mm Outer Steel Plate Cover.

which helps to overcome the limitations posed by the uncertainties with regard to a series of experiments conducted over a wide range of hydrogen blast energies as the resultant waves may get focused at the structural wall and excite a local structural vibration mode of the barrier structure that must be analyzed systematically to provide adequate safety measures.

2. Objectives and scope of hydrogen blast experiments in test-chamber

The objective of this study is to quantify the hydrogen charge that may be safely used to successfully carry out repeated hydrogen explosion experiments within the composite structure test-chamber facility. This was accomplished with the experimental data obtained from controlled hydrogen explosion tests carried out for a series of experiments with 1 g, 2 g, 4 g, 8 g and 16 g hydrogen charges within the test-chamber. The feasibility to perform combustion tests for different hydrogen charges is examined with a simplified analytical structural evaluation of the test-chamber to ascertain its limiting impulse and quasi-static pressure capacity and the associated limiting transient dynamic response for various postulated and identified structural failure modes. The evaluation is further used to assess the available margins such that the test-chamber structure is ensured to remain within the elastic limit for the identified hydrogen blast tests. This is accomplished by the transient dynamic characterization of the test-chamber structure and the observed hydrogen blast wave with the limited test data collected during the initial blast tests at lower hydrogen charges up to 8 g. After ensuring sufficient margin between the observed blast pressure impulse as compared to the limiting impulse and a large factor of safety between the limiting peak displacements of the test-chamber structure and the corresponding observed peak elastic displacements, guidelines are developed for safely conducting the targeted blast test for 16 g hydrogen charge. Subsequently the test data within the elastic limit as obtained from the controlled hydrogen blast test is confirmed with the detail three-dimensional transient dynamic finite element evaluation of the composite test-chamber structure. Finally, the limiting impulsive and quasi-static over-pressurization load that the test-chamber will be able to withstand safely is determined more precisely with the analytically and experimentally validated finite element model and confirmed with the limiting values as predicted with the simplified models in the initial phase of the work. The emphasis in this work is to evolve simple validated analytical-experimental procedures for blast resistance evaluation of structures that may be utilized to supplement detail finite element computations.

3. Simplified analytical analysis of test-chamber composite structure for hydrogen blast experiments

For the proposed blast experiments with 1 g, 2 g, 4 g, 8 g and 16 g hydrogen charges; during the planning stage it was desirable to establish in advance the adequacy of the composite test-chamber structure (Fig. 1) for its limit load carrying capacity. The simplified computational work in addition was also useful for evaluating the structural performance of the test-chamber structure for the 16 g combustion test after experiments were completed up to 8 g of hydrogen combustion. This simplified limiting conservative computation for the structural safety assessment of the test-chamber structure has been useful to get insight in to the structural behavior and appropriate engineering judgments could be arrived for the continued future combustion experiments while the detail numerical finite element transient simulations were in progress.

A computer program **COLLAPSE** has been developed which is useful for estimating the dynamic collapse behavior of the slabs and plates that are subjected to quasi-static ultimate pressure and impulse due to blast load based on the formulations available in [2,5]. Baker's formulation uses the strain energy and kinetic energy of the structural systems to predict the initiation of failure due to the sustained quasi-static pressure for longer durations compared to the natural period of the structure. Another limiting condition computed by this model is the estimation of the impulsive behavior of the structure for short duration impulses due to blast or combustion events within the confined enclosures. This is governed by the kinetic energy induced in the structural system. Baker's model is based on small deformation elasto-plastic theory and failure is identified with formation of hinge mechanism in