Vibro-acoustic Analysis of NASA's Space Shuttle Launch Pad 39A Flame Trench Wall

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ABSTRACT

A vital element to NASA's manned space flight launch operations is the Kennedy Space Center Launch Complex 39's launch pads A and B. Originally designed and constructed in the 1960s for the Saturn V rockets used for the Apollo missions, these pads were modified above grade to support Space Shuttle missions. But below grade, each of the pad's original walls (including a 42 feet deep, 58 feet wide, and 450 feet long tunnel designed to deflect flames and exhaust gases, the flame trench) remained unchanged. On May 31, 2008 during the launch of STS-124, over 3500 of the 22000 interlocking refractory bricks that lined east wall of the flame trench, protecting the pad structure were liberated from pad 39A.

The STS-124 launch anomaly spawned an agency-wide initiative to determine the failure root cause, to assess the impact of debris on vehicle and ground support equipment safety, and to prescribe corrective action. The investigation encompassed radar imaging, infrared video review, debris transport mechanism analysis using computational fluid dynamics, destructive testing, and non-destructive evaluation, including vibro-acoustic analysis, in order to validate the corrective action.

The primary focus of this paper is on the analytic approach, including static, modal, and vibro-acoustic analysis, required to certify the corrective action, and ensure integrity and operational reliability for future launches. Due to the absence of instrumentation (including pressure transducers, acoustic pressure sensors, and accelerometers) in the flame trench, defining an accurate acoustic signature of the launch environment during shuttle main engine/solid rocket booster ignition and vehicle ascent posed a significant challenge. Details of the analysis, including the derivation of launch environments, the finite element approach taken, and analysis-test/launch data correlation are discussed. Data obtained from the recent launch of STS-126 from Pad 39A was instrumental in validating the design analysis philosophies outlined in this paper.

Vibro-Acoustic Analysis of NASA's Space Shuttle Launch Complex 39, Pad A Flame Trench Wall

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Abstract

A vital element to NASA's manned space flight launch operations is the Kennedy Space Center (KSC) Launch Complex 39's launch pads A and B. Originally designed and constructed in the 1960s for the Saturn V vehicle that was used for the Apollo missions, these pads were modified to support Space Shuttle missions (Figure 1). Each pad's original walls (including a 42 foot deep, 58 foot wide, and 450 foot long tunnel known as the flame trench (Figure 2), was designed to deflect flames and exhaust gases) remained unchanged. On May 31, 2008, during the launch of STS-124, over 3,500 of the 22,000 interlocking refractory bricks that line the east wall of the flame trench (used to protect the pad structure) were liberated from the east wall of pad 39A.

The STS-124 launch anomaly generated an agency-wide initiative in order to determine root cause, assess vehicle safety, ground support equipment (GSE) safety and reliability, and to determine corrective action. The investigation encompassed radar imaging, infrared video review, debris transport evaluation, computational fluid dynamics (CFD), non-destructive evaluation (NDE) and vibro-acoustic analysis in order to validate the corrective action.

The primary focus of this paper is on the analytic approach, including static, modal, and vibro-acoustic analysis, required to certify the design modification, and ensure integrity and operational reliability for future launches. Due to the initial absence of instrumentation (including pressure transducers, acoustic pressure sensors, and accelerometers) in the flame trench, defining an accurate signature of the launch environment during shuttle main engine/solid rocket booster (SSME/SRB) ignition and vehicle ascent, posed a significant challenge. Details of the analysis, including the derivation of launch environments, the analysis approach taken, and analysis-test/launch data correlation are discussed. Data obtained from the recent launch of STS-126 from Pad 39A, was instrumental in validating the design analysis philosophies outlined in this paper.

BACKGROUND

The construction of Launch Complex 39's Pad A at Kennedy Space Center was completed in 1965. Pad 39A's flame trench, a holdover from the Apollo era, has sustained 83 total vehicle launches (as of STS 126), including 12 launches from Saturn V during the Apollo era and more than 71 launches during the Space Shuttle era. During the course of the STS-124 launch, an unprecedented quantity of refractory bricks from the east wall on the SRB side of the flame trench was liberated (Figure 3). Consequently, a comprehensive assessment of the flame trench launch environment in order to effectively understand the failure mechanism of the wall, as well as the certification of the corrective action including the repair and modification of the flame trench wall had to be performed.

FLAME TRENCH REPAIR AND MODIFICATION

It was determined that the predominant cause of the refractory brick failure was due to the degraded epoxy bond between the bricks and the underlying concrete wall, coupled with corrosion to the steel reinforcing clips that helped to secure the bricks to the wall (Figure 4). Due to the degraded bond condition, the low frequency transient pressure pulse that results from the SRB ignition and subsequent exhaust flow oscillation, caused the bricks to pull away and separate from the wall (Figure 5).

The flame trench repair/modification consisted of the replacement of approximately a 98 by 25 foot section of damaged bricks from the east side, and 80 by 25 foot section of intact refractory bricks from the west side with "Fondu Fyre" (a heat resistant concrete developed during the Apollo space program). The Fondu Fyre was applied in 61 by 75 inch interlocking panels (Figure 6). Each panels hexagonal steel reinforcing grid structure was anchored into the underlying concrete wall with 16 evenly spaced steel anchors. In order to account for the degradation of the existing concrete-brick epoxy bond, the remaining refractory bricks were mechanically anchored to the underlying flame trench wall.

DERIVATION OF LAUNCH ENVIRONMENT

Prior to the launch of STS-126, there were no launch data measurements available from the flame trench. In order to properly design the modifications, it was important to understand and quantify the effects of the launch environment responsible for the STS-124 damage in the area of the flame trench repair. Due to the lack of area specific data, a representative launch environment needed to be derived from available measurements. Launch data based power spectral densities (PSDs) and historic launch data from neighboring locations on Pads 39A and B, as well as analytic data derived from flame trench CFD analysis, were reviewed/compared. Subsequently, static design pressures and power spectral densities were derived from this comparison. These data were used in the analysis of the flame trench repair and modification.

Static Design Pressures

Dynamic pressures obtained from the output of 14 pressure sensors located in the west SRB exhaust well during the launch of STS-9 were processed in terms of power spectral densities (PSDs). The root-mean-square (RMS) of the statistical 3 sigma limit curve was used to calculate an equivalent static design pressure.

The start-up phase of an SRB, including the rapid pressure build up in the motor chamber resulting in an ignition overpressure (IOP) and subsequent wave propagation from the launch pad, results in a low frequency transient pressure oscillation (Figure 5). The magnitude of this negative pressure pulse measured at the SRB exhaust well was reviewed for 29 launches from Pad A and 27 launches from Pad B. The measured pulse from STS-124 was consistent with the 56 historic launches reviewed during the assessment.

In addition to the evaluation of static pressure pulses from historic launch measurements taken at neighboring locations on Pads A and B, data from CFD analysis performed by NASA AMES/KSC was reviewed. The CFD data identified the above mentioned low frequency surge propagating through the flame trench during SSME and SRB ignition and subsequent vehicle ascent.

The equivalent static load obtained from STS-9 launch data, the low frequency transient measured during the launch of STS-124, along with the CFD data provided by NASA AMES/KSC were compared and analyzed in order to evaluate a static pressure for use in the design of the flame trench repair and modification (Figure 5).

The derivation of launch environments via the scaling of historic data showed agreement between the two methods. The CFD data in the area of the repair was approximately 38% less than scaled historical data. Since the data used to derive the launch environment in the flame trench was taken from a location closer to the energy source it was expected to be higher than the area specific CFD data. Due to their conservative nature, and given the high degree of correlation between the two spatial scaling methods, the spatially scaled launch environment was used for the analysis. Also, due to the uncertainty of the environment scaling a measurement uncertainty factor was employed in application of the final static pressure environment.

Acoustic Design Pressures

A launched-induced pressure acoustic environment in the form of a PSD was needed as input for the random response analysis. As with the static pressure environment, there was no available launch data in the area of the flame trench. The input PSD acoustic pressure loads needed to be derived from available launch data from adjacent Pad A locations. The input PSD used was the upper bound of PSDs processed from approximately 4.5 seconds of launch data obtained from the side flame deflector during STS-3 and STS-124, processed from 0 to 100 Hertz. Due to the nonstationary and short time duration aspects of the launch data the resulting PSD was multiplied by a low frequency correction factor before input into the analysis.

LAUNCH-INDUCED VIBRO-ACOUSTIC ANALYSIS

The typical structural subsystems of the flame trench, including the repair and modification, were modeled using the finite element analysis (FEA) code MSC/NASTRAN (Figures 7 and 8). These systems include a section of the main launch pad structure with its underlying steel reinforcement known as a catacomb cell, a section of Fondu Fyre, and its underlying hexagonal steel reinforcing grid structure. It was determined that the repair needed to be designed to withstand the launch environment in a fully degraded bond condition. Therefore, for design purposes a single Fondu Fyre panel and a representative catacomb cell were modeled as having no structural interaction other than through the sixteen steel anchors supporting the grid steel matrix. The mass effects of the remaining Fondu Fyre panels, as well as the refractory brick, were accounted for using nonstructural lumped mass elements.

Modal Analysis

Modal Analysis was performed on the representative catacomb cell, on a single grid steel reinforced Fondu Fyre panel and on the simulated interaction of the catacomb cell and debonded panel. The natural frequencies of the Fondu Fyre panel were evaluated to ensure that a panel with a degraded bond would not be excited by the launch environment.

Similarly bending modes of the flame trench wall were compared to launch spectra in order to evaluate potential modal coupling that may further any potential debond condition.

Structural Analysis

In order to understand the effects of a Shuttle launch on the repaired wall, a thorough structural analysis was performed using the finite element analysis code MSC/NASTRAN. This analysis included the transient pressure effects and the launch-induced acoustic effects experienced in the flame trench at the time of ignition and vehicle ascent. In order to evaluate the structural integrity of a debonded Fondu Fyre panel, the transient pressure pulse derived above was applied as a static load present throughout the duration of the vehicle ascent, as opposed to the short duration of the transient pressure pulse actually present in the flame trench environment. The results of the negative pressure on the repair were coupled with the results of a random response FEA using the launched-induced acoustic environment in the form of a PSD as derived above.

POST STS-124 INSTRUMENTATION

In order to certify the corrective action, and validate the analytic approach, instrumentation was placed within the SRB side of the flame trench for the launch of STS-126. Pressure sensors (both pressure transducers and acoustic pressure sensors) as well as accelerometers, were placed along the east and west walls of the SRB flame trench.

Pressure Measurements

Different types of pressure instrumentation were used during the launch of STS-126. Pressure transducers were mounted on corresponding locations on both the east and west walls of the flame trench. These pressure transducers as well as higher frequency piezoelectric acoustic pressure sensors were also located along the bottom of the main SRB Flame Deflector. Pressure data from these locations was instrumental in quantifying the launch environment, and thus the validation of the assumptions used in the analysis-based certification of the flame trench repair.

Accelerometer Measurements

Highly sensitive single axis piezoelectric accelerometers, mounted normal to the flame trench wall, were used to measure the acoustic response of the composite flame trench wall at various locations along the SRB flame trench. These accelerometers were mounted on corresponding locations on the back sides of both the east and west walls of the flame trench, in an area known as the catacomb, in order to protect them from the launch environment. The results from these accelerometers were used in determining the bending modes of the composite flame trench wall.

Data Acquisition

Initial recording of the time history pressure sensor and accelerometer data were made around the time of launch. The data from the pressure transducers and accelerometers was sampled at 9,600 samples per second with a range up to 100 psia, and +/-10gs respectively. Acoustic pressure data was sampled at 19,200 samples per second with a range up to 120 psia. These time histories were then reduced to raw oscillograms which were further reduced to significant time intervals (10 seconds before to 20 seconds after SRB ignition) for further post-processing.

LAUNCH / ANALYSIS CORRELATION

Launch Environment Correlation

The new instrumentation in place for the launch of STS-126 provided the opportunity to validate the assumptions made with regard to the launch environments used in the analysis of the flame trench repair and modification. The unique nature of the ignition and subsequent ascent of the Space Shuttle make spatially scaling of the launch environment extremely unreliable. Certain relatively neighboring areas of the launch pad may have exposures to entirely different launch environments. Some areas may be subject to plume effects in which they are impinged upon by both solid and gaseous launch products, while other seemingly adjacent areas may only experience launch-induced acoustic effects. Similarly, one area may experience a more pronounced environment due to IOP effects than its spatially similar counterpart. Overall, the assumptions made in the design of the post STS-124 modifications proved adequate. The spatial scaling of both PSDs and time histories of historic launch data, in attempt to derive the negative transient pulse at the location of the repair, overestimated the local launch environment by approximately 40%. Conversely, time shifted CFD data underestimated the IOP pulse by approximately 13%.

Launch Response Correlation

General agreement between predicted and measured frequencies and mode shapes of the composite wall is very good. In reviewing the PSDs processed from the time history data obtained from the accelerometers, it was obvious that there were two bending modes excited by the launch environment. These two measured modes correlated well with predicted values (Figure 9). The predicted primary bending mode, as a result of normal modes analysis, was approximately 4%

above the primary bending mode of flame trench wall. The secondary bending mode predicted by analysis, differed by less than 1% from the actual as determined through launch data processing. In reviewing the PSDs processed from the time history data obtained from the pressure transducers, it seems that there is minimum potential for coupling between the launch environment and the natural frequencies of a debonded panel.

CONCLUSION

The repair and modification of the Pad A flame trench has provided a unique opportunity to further understand the effects of a Space Shuttle launch on its surrounding launch structure. The upcoming launch of STS-119 will provide another series of data points in attempt to certify the corrective action. Though it appears that there is limited potential to excite a Fondu Fyre panel in a state of total bond degradation additional data is required to fully understand its potential response. The application of additional accelerometers embedded into the Fondu Fyre is currently being discussed. The data from these sensors in comparison to corresponding sensors in the catacombs should help to quantify the launch effects on the Fondu Fyre itself, in addition to the understanding of the composite flame trench wall.

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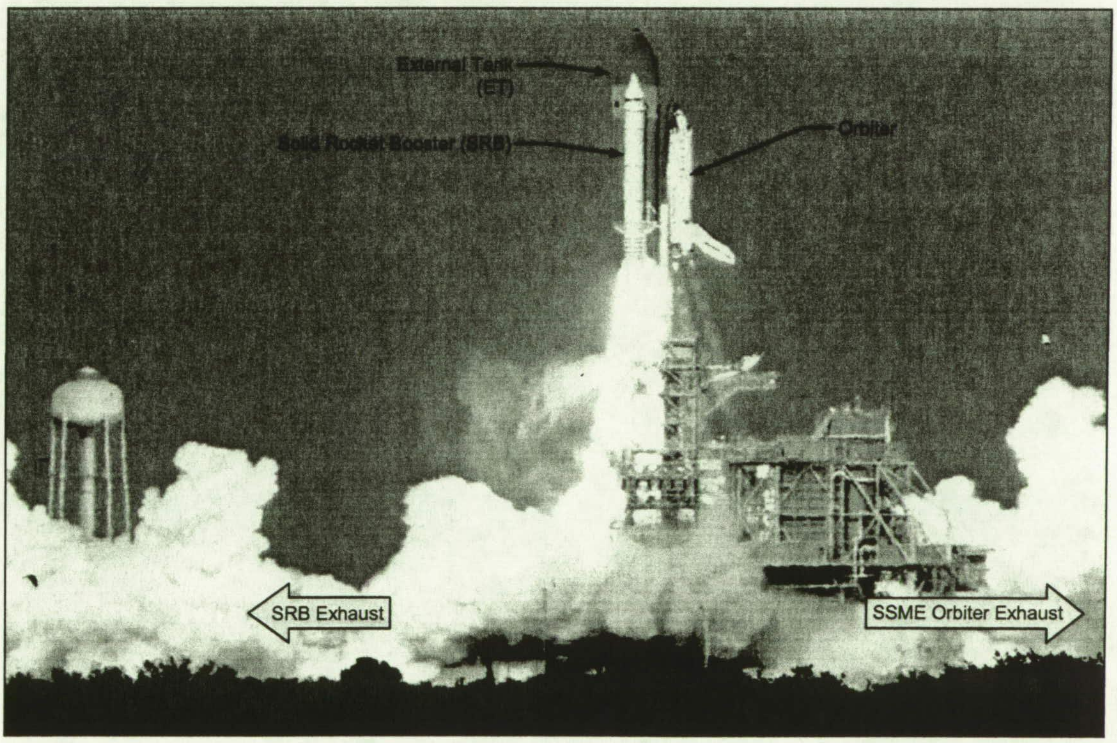

Figure 1. Space Shuttle Launch

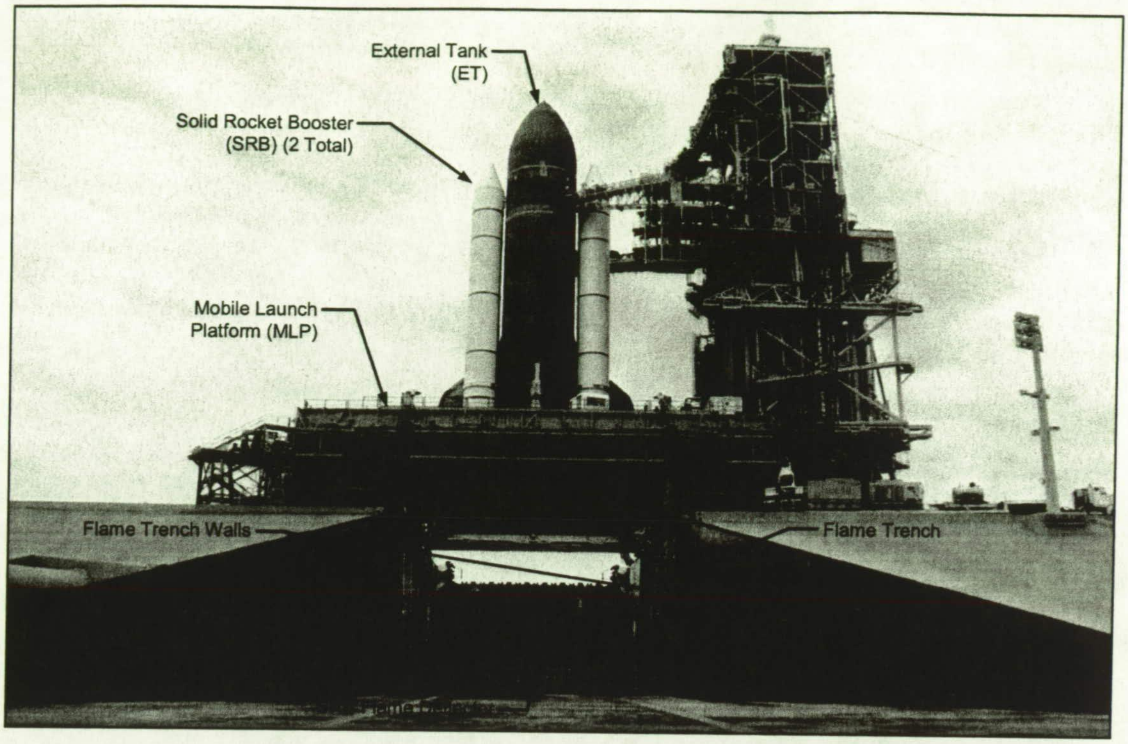

Figure 2. Launch Complex 39 Pad A SRB Flame Trench – Looking South

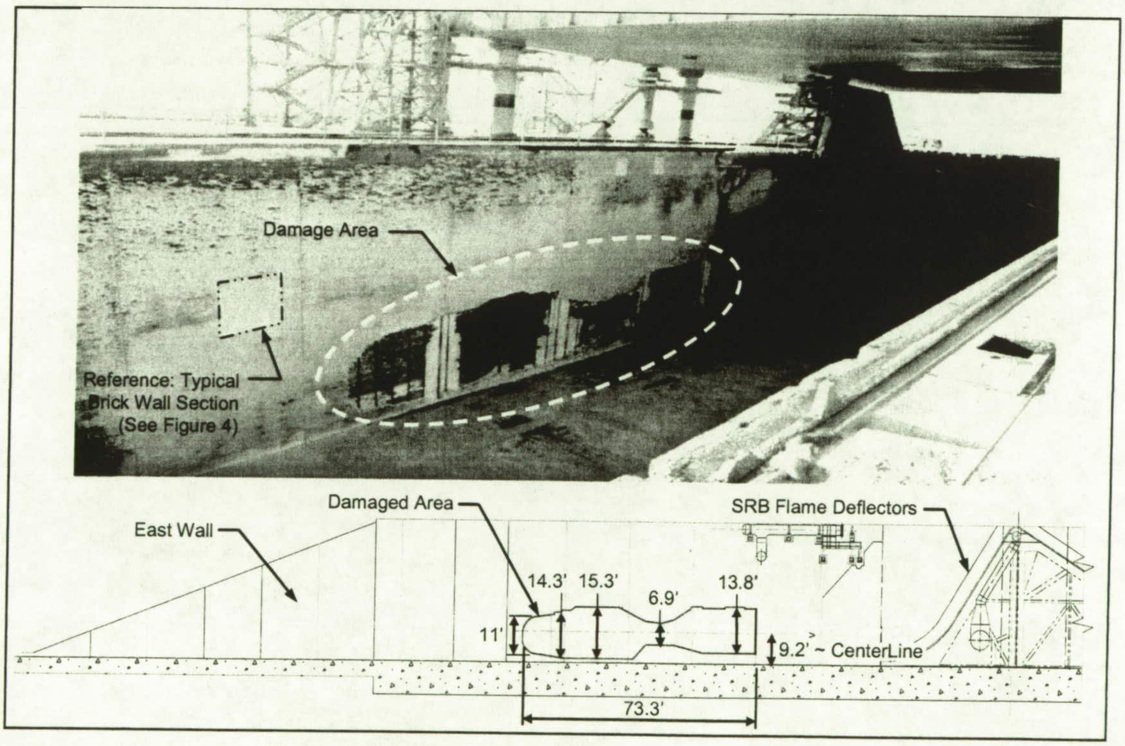

Figure 3. Launch Complex 39 Pad A Flame Trench Post STS-124 Damage

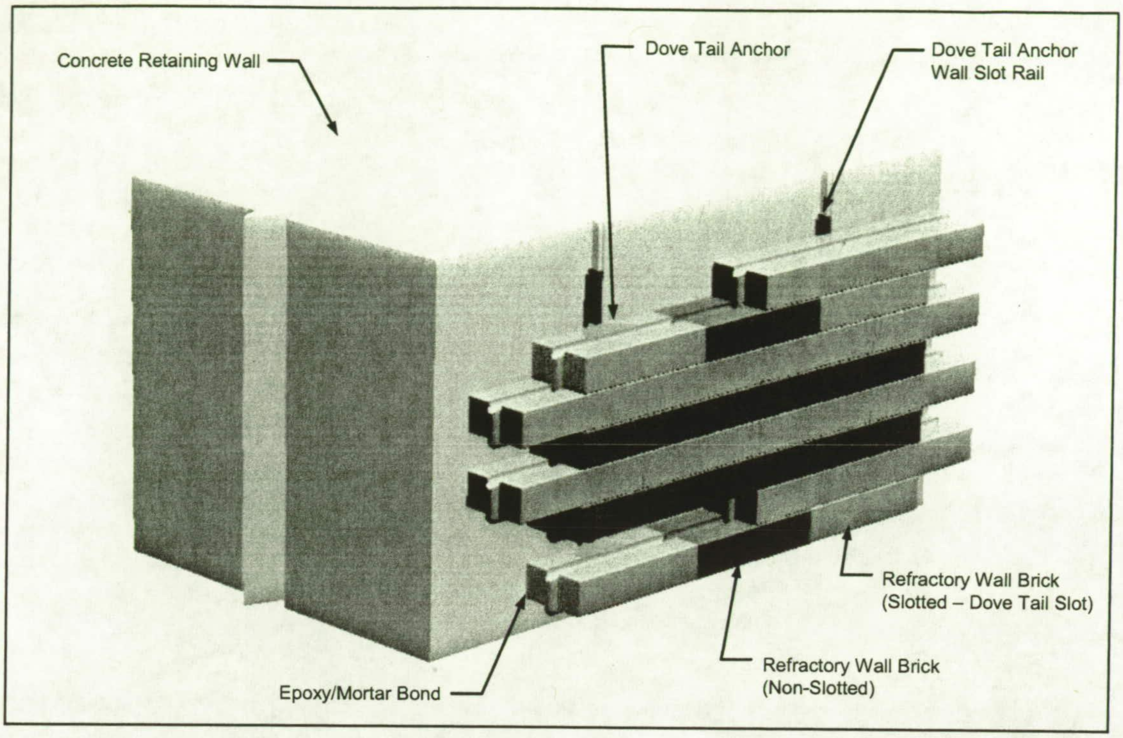

Figure 4. Typical Refractory Brick Configuration

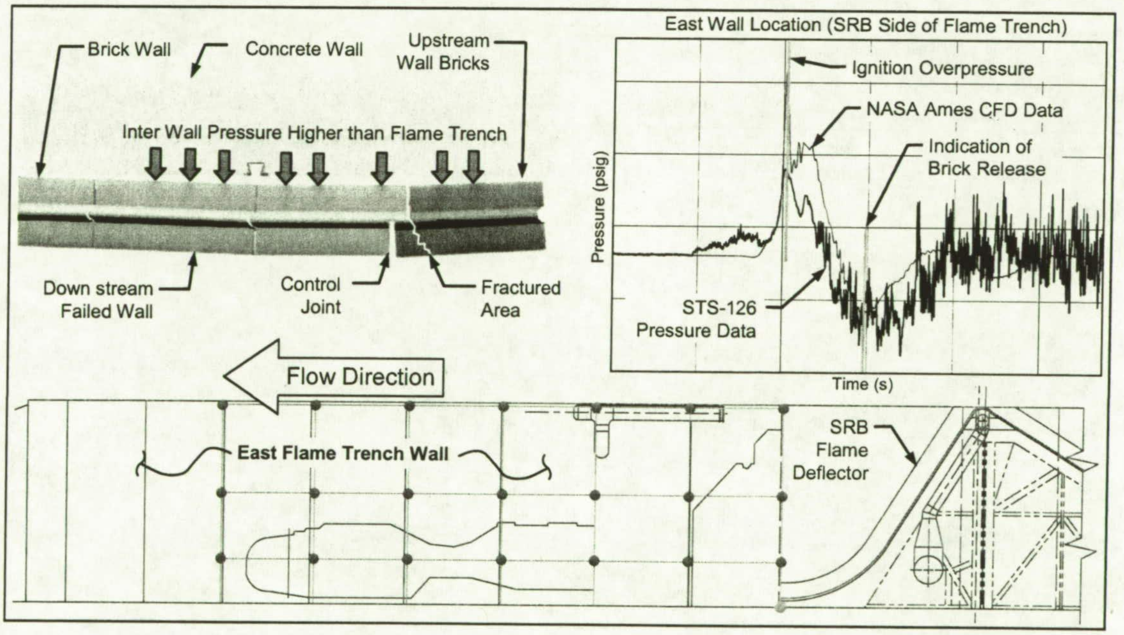

Figure 5. STS-126 Data/CFD Results of IOP, and Resulting Negative Pressure

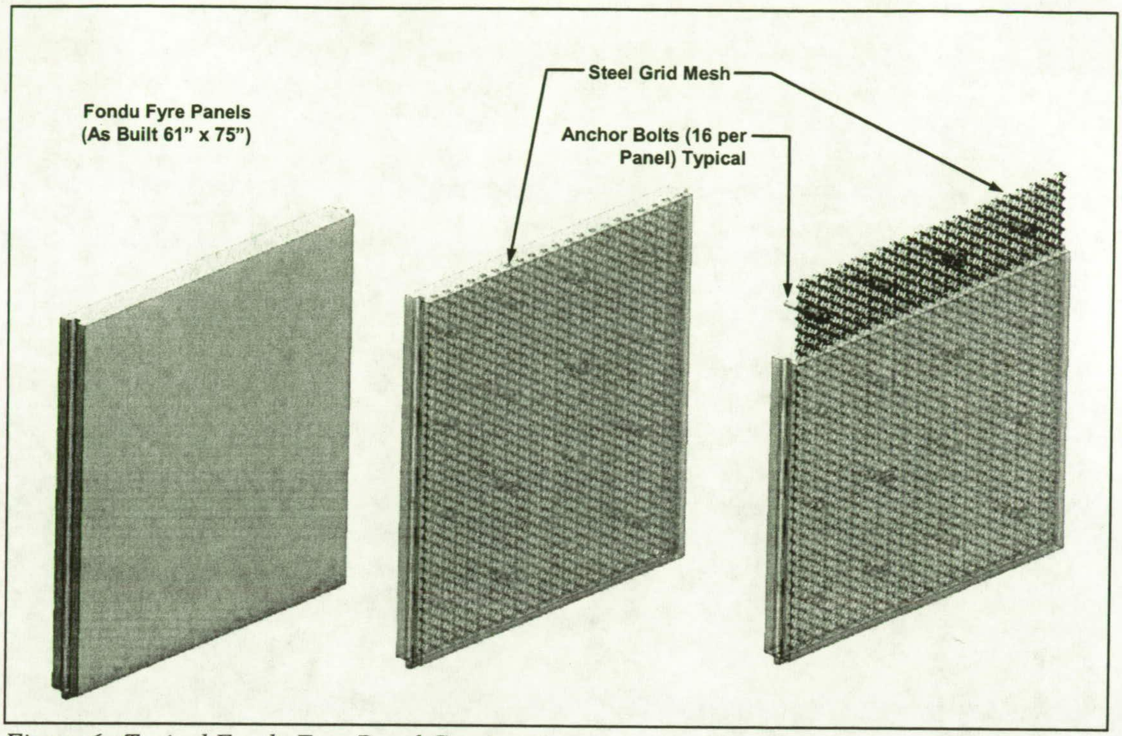

Figure 6. Typical Fondu Fyre Panel Construction

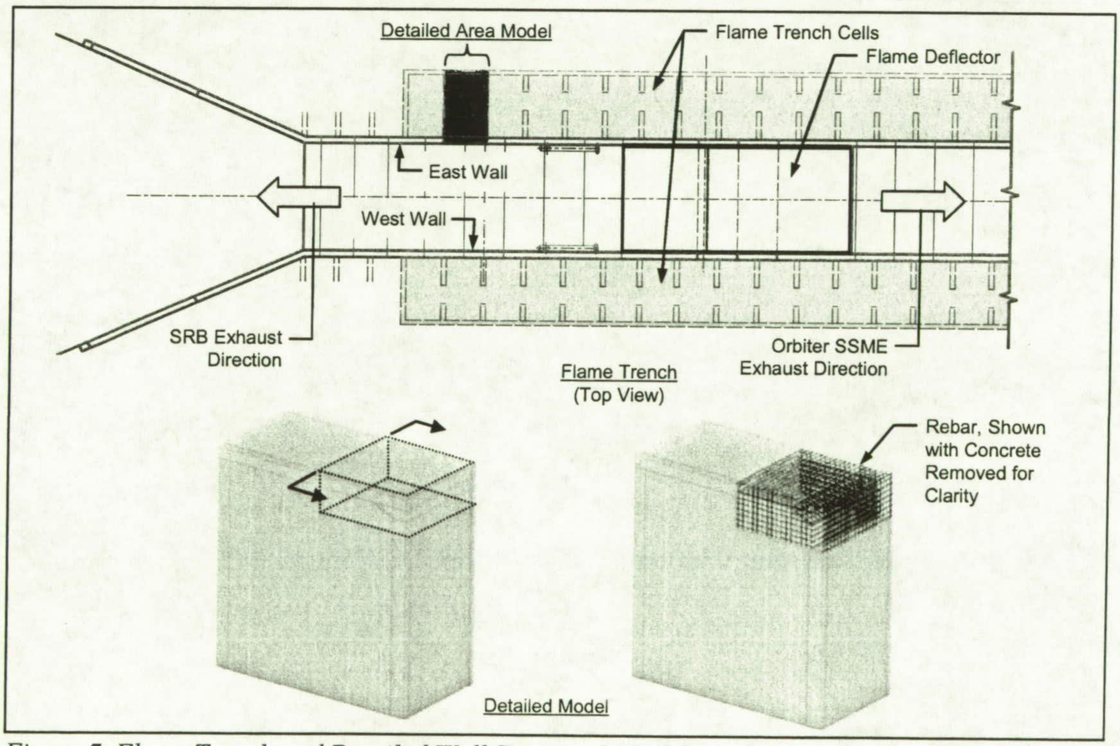

Figure 7. Flame Trench and Detailed Wall Structural Model

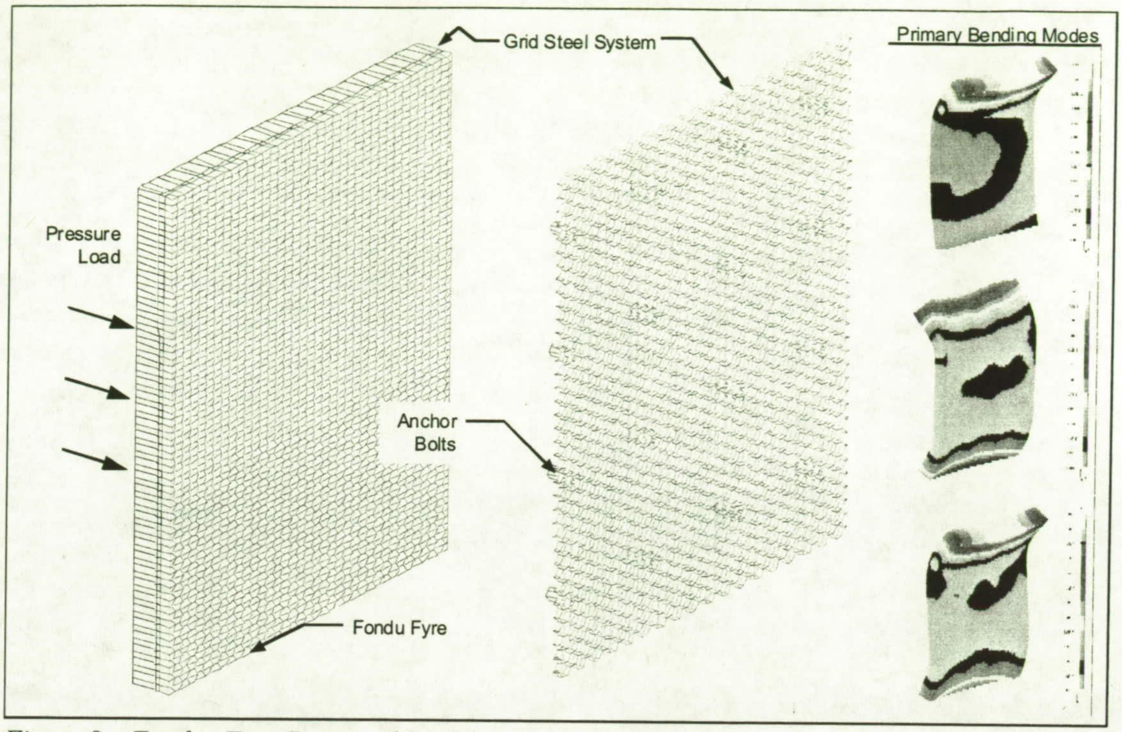

Figure 8. Fondue Fyre Structural Model, and Primary Bending Mode Shapes

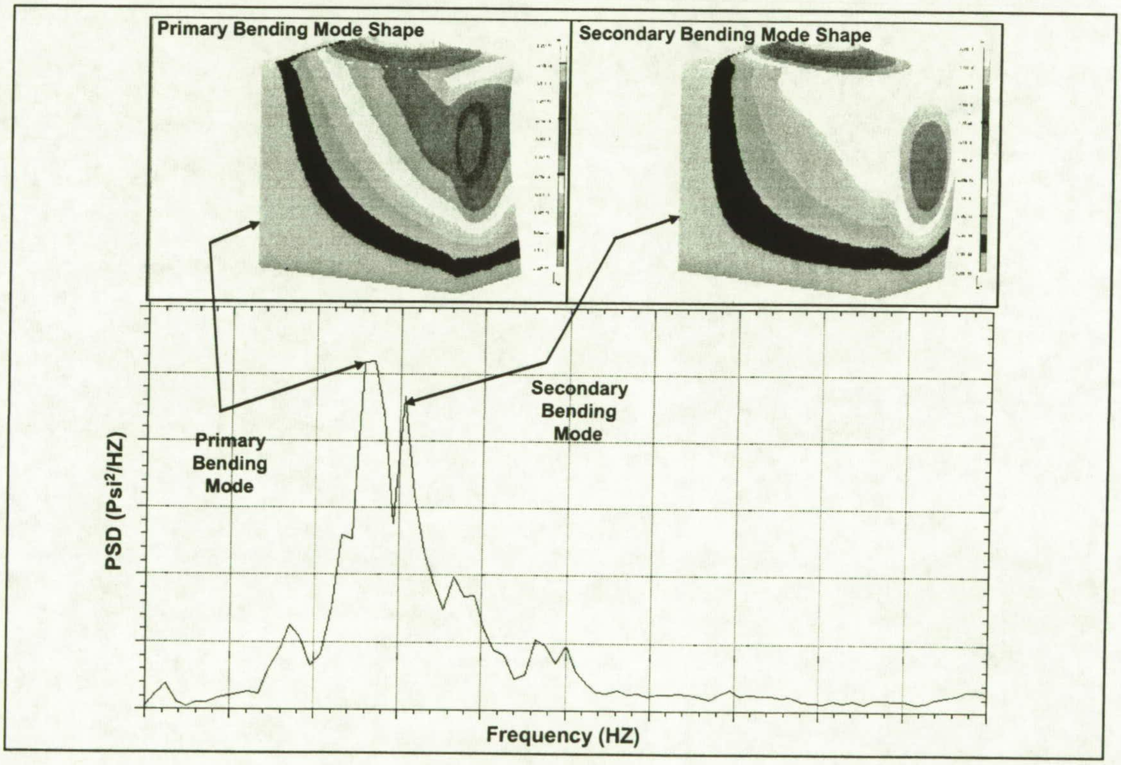

Figure 9. Catacomb Cell Wall Mode Shapes