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Structural mechanics of a mortar launched IR dome

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Abstract

This paper presents a case study of the development of a Zinc Sulfide IR dome for a mortar-launched projectile. As a case study, it demonstrates the value of analysis as a means to obtain insight and derive solutions to design problems. It also describes problems solved by a variety of finite element codes: SAAS-3, EPIC-2, and NASTRAN. The paper discusses the determination of inertia loads, joint design, bonding of the dome to the attachment ring, verification testing, mortar test firings, and post test analyses. The paper discusses various FEM analyses performed during the development. Inertia load factors used for design were derived from a transient dynamic response analysis of launch and muzzle exit. Structural integrity of the brittle ceramic dome material was demonstrated by a detailed FEM stress analysis of the joint. This analysis considered modeling techniques for threaded and bonded joints. This FE model was also utilized to define an equivalent proof pressure test to simulate the inertia load. Initial tests resulted in the failure of both the dome and the attachment device of internal ballast. Additional analyses were conducted to evaluate modal response and impact. These analyses established the internal ballast as the cause of failure, and subsequent successful dome test firings validated the analyses.

Introduction

While predicting and controlling deformations of optical systems is necessary to achieve a desired level of performance, equally important is configuring a design that withstands the mechanical load environment. In dealing with military systems, these environments typically consist of shock and vibration caused by transportation, aircraft captive-carry, and tactical missile and launch vehicle flight. Recent development of IR guided projectile systems has extended design requirements for optical-like elements to include inertia loads of the order of 10,000 g's. At these levels of inertia load, designing components that have adequate strength is not straightforward, and structural mechanics becomes an essential design tool.

The structural analyses that have been performed for an IR dome on a mortar-launched guided projectile are described in this paper with the hope that it will provide some insight to designers and analysts of future optical systems.

The IR dome is an optical element that serves as an IR transparent cover on the forward end of the projectile. The projectile and dome configurations are depicted in Figure 1. The dome is hemispherical in shape, 0.093 inch thick, and made of Zinc Sulfide. Zinc Sulfide is a brittle material that requires accurate prediction of the stress distribution. Finite element analyses were performed to predict:

1) muzzle exit dynamic response
2) stresses in the Zinc Sulfide dome joint
3) transient dynamic stresses caused by impact at the projectile base

The details of the analyses are described in the following sections.

Dynamic analysis of muzzle exit loads

The projectile is fired from a standard 4.2 inch Army mortar. The worst case acceleration history corresponding to a maximum explosive charge is shown in Figure 2. The peak setback "g" level is 11,000 g's. The duration of the acceleration pulse is sufficiently long, compared to the projectile dynamic characteristics, that no dynamic amplification of the 11,000 g peak occurs. Consequently, the IR dome experiences a compressive 11,000 g inertia load.

Dynamic amplification does occur during the exit of the base of the projectile from the mortar muzzle. Referring to Figure 2, an acceleration of 2500 g exists as the projectile starts to leave the mortar at time t_1. This acceleration decreases to zero at time t_2. The interval, $t_2 - t_1$, during which the acceleration of the projectile decreases to zero, is in the range of 0.05 - 0.4 milliseconds. This sudden unloading of the projectile causes dynamic excitation and produces a large tensile inertia load on the dome.

The dynamic response was analyzed by using a NASTRAN (Ref. 1) beam and lumped mass model of the projectile. An accelerating force producing a 2500 g acceleration was applied to the base of the model, along with the 2500 g equilibrating inertia load. The force on the base was linearly decreased to zero over a time interval T. Peak dome accelerations were determined for intervals, T, of 0.05, 0.10, and 0.20 milliseconds. The results are plotted in Figure 3. The results show that the dome response is sensitive to the decay time, T. For subsequent analyses, a 8750 tensile inertia load factor corresponding to a 0.05 ms decay time was selected.

Stress analysis of dome attachment joint

The joint that attaches the dome to the body of the projectile must be designed to give an acceptable stress concentration in the dome. Because the dome material, Zinc Sulfide, is a brittle polycrystalline material, it has low ductibility and is weak when subjected to tensile stress. These characteristics make predicting and controlling joint stresses the key to a successful design. The joint design is depicted in Figure 4.

Accurate prediction of stresses in the joint was obtained by a finite element stress analysis performed with the SAAS-3 program (Ref. 2). The finite element mesh used for the stress analysis is shown in Figure 5. The model considers the details of the actual geometry and materials: Zinc Sulfide, epoxy adhesive, aluminum.

The stress analysis was conducted for an 11,000 g load factor in the aft direction (forward acceleration) and 8,750 g load factor in the forward direction (aft acceleration). The results showed that the 11,000 g condition was not critical, because the dome material was put in a state of compression, in which state brittle materials are very strong. The load acting in the forward direction caused a tensile stress in the Zinc Sulfide of 3826 psi. The estimated design allowable for Zinc Sulfide is 7500 psi. Typically, the structural integrity of a brittle material is defined in terms of a statistical probability of failure (or conversely, reliability) as determined by Weibull statistical strength theory. This analysis was not performed for the dome because the stress was much lower than the design allowable and occurs over a small region. Consequently, the dome probability of failure is small by inspection. For further information, details of Weibull analysis can be found in References 3, 4, and 5.

The finite element model was also used to evaluate the dome-to-retaining ring bond requirements. Three types of bonds were evaluated based on stiffness and strength. Stresses in the bond and dome were determined for assumed bond moduli of $0.5\text{x}10^6$ (epoxy), $0.1\text{x}10^6$ (semi-rigid acryllic), and $1.0\text{x}10^4$ (flexible acryllic). These studies showed that the epoxy (EA-934) bond was the best choice. The epoxy produced acceptable stresses in the dome and had sufficient shear strength to withstand the inertia loads. The RTV bond produced the largest stress in the dome and did not have sufficient shear strength. The acryllic bond also did not have sufficient shear strength. Bond shear strengths were determined from lap shear specimens consisting of polished Zinc Sulfide surfaces bonded to aluminum. The test results are summarized in Table 1.

TABLE 1. Strength of Bond Lap Shear Specimens

Bond Material	Strength* psi
EA-934 epoxy	3483
Dymax semi-rigid acryllic	1947
Force 1 flexible acryllic	1467

*average of three specimens

The structural integrity of the dome was substantiated by conducting pressure tests that simulated the inertia loads. Both internal and external pressures equivalent to the forward and aft inertia loads were applied without failure.

Dome test firings

Two ballistic test vehicles with domes were fired from mortars in early 1983. Both tests resulted in failure of the domes. These failures prompted a review of design conditions, analyses, and material characteristics in order to explain and correct the cause of failure. The initial review found nothing that could explain the failures. Further investigation revealed that an internal ballast weight had broken loose and impacted the projectile base. This potential cause of failure was evaluated by conducting an impact analysis with the EPIC-2 program (Reference 6).

The model of the projectile base, body, and dome, as well as the impacting weight depicted in Figure 6, was used to determine the transient dynamic stresses propagated to the dome. The analysis predicted a 22 ksi tensile stress would occur in the dome 1.5 milliseconds after impact. This stress was well above the strength of the dome material.

The cause of the ballast weight failure was eliminated and a third test projectile fired. The dome survived this test. Figure 7 shows the projectile and dome just after exiting the mortar.

Conclusions

Structural mechanics has an important role in the design of guided projectile optical systems. The IR dome considered in this paper, while not strictly an optical element, is considered representative of a typical optical element. Structural mechanics has been shown to be a useful tool for establishing design requirements, configuring a design, and evaluating structural failures. The finite element programs mentioned in this paper, NASTRAN, SAAS-3, and EPIC-2, are but a few of the codes available. With these finite element codes, the solution of complex static and transient dynamic problems is routine. Let us not forget, however, that these tools are only as useful as the skill of the person who wields them.

References

1. NASTRAN, The MacNeal-Schwendler Corporation, April 1982.

2. Crose, J. and Jones, R., SAAS-3, Air Force Report No. SAMSO-TR-71-103, June 1972.

3. Wurst, J. and Strecker, C., "The Design of a Proof Test for ZnSe," Proceedings of the Fourth Annual Conference on Infrared Laser Window Materials, DARPA, November 1974.

4. Speare, J., "Structural Analysis of High Power Laser Window Zinc Selenide Panes," Proceedings of the Fifth Annual Conference on Infrared Laser Window Materials, DARPA, December 1975.

5. Neal, D., Spiridigliozzi, L., "An Efficient Method for Determing the 'A' and 'B' Design Allowables," Proceedings of the Army Symposium on Solid Mechanics, Report AMMRC MS 82-4, September 1982.

6. EPIC-2, A Computer Program for Elastic-Plastic Impact Computations in Two Dimensions Plus Spin, Army BRL Report ARBRL-CR-00373, June 1978.

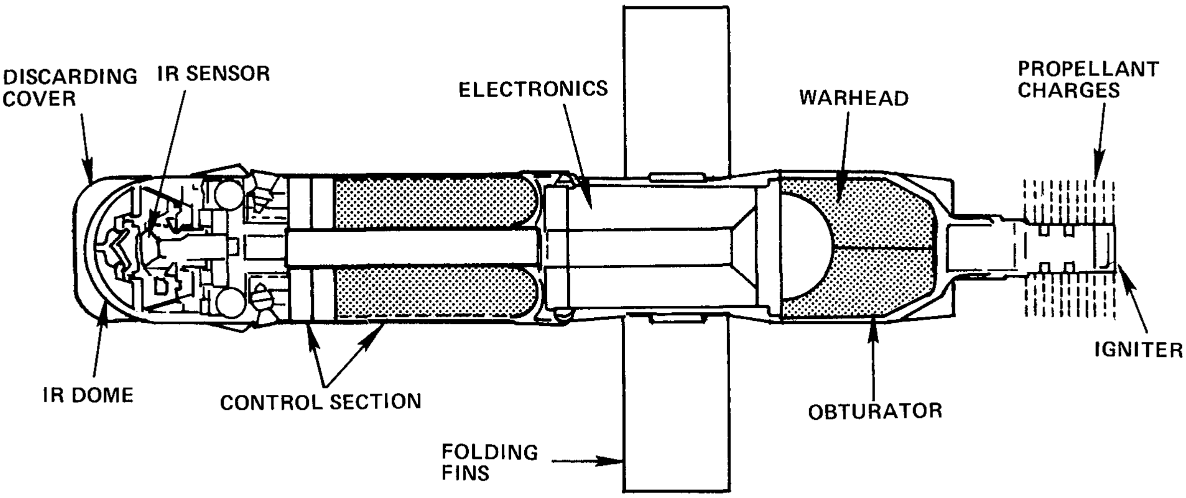

Figure 1. Mortar Launched Projectile

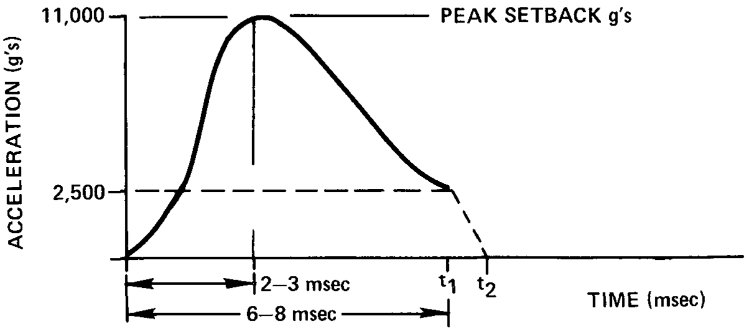

Figure 2. Acceleration Time History

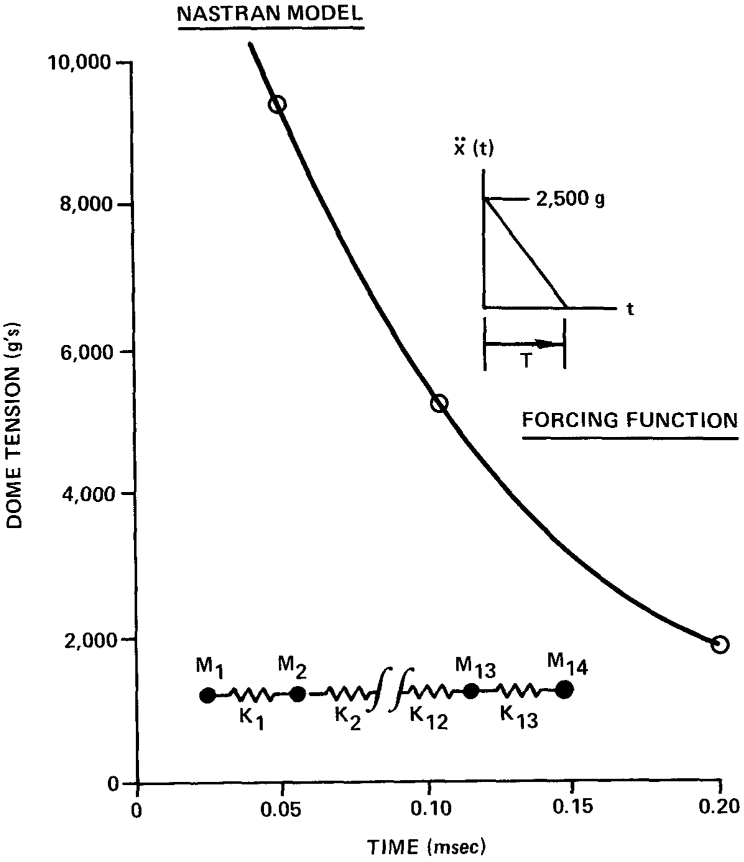

Figure 3. Dome Response to Muzzle Exit Decay Time

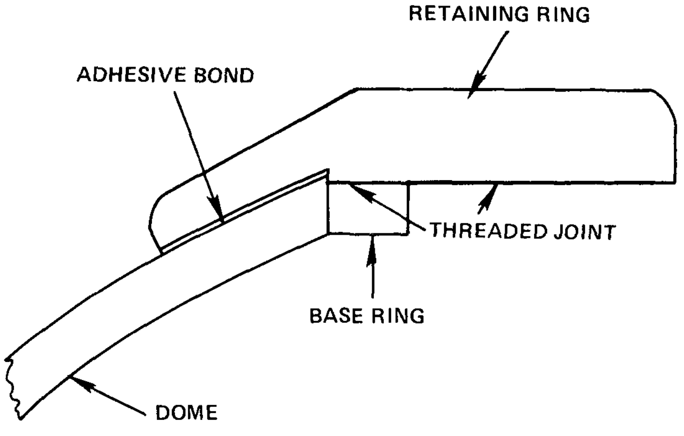

Figure 4. Joint Design Configuration

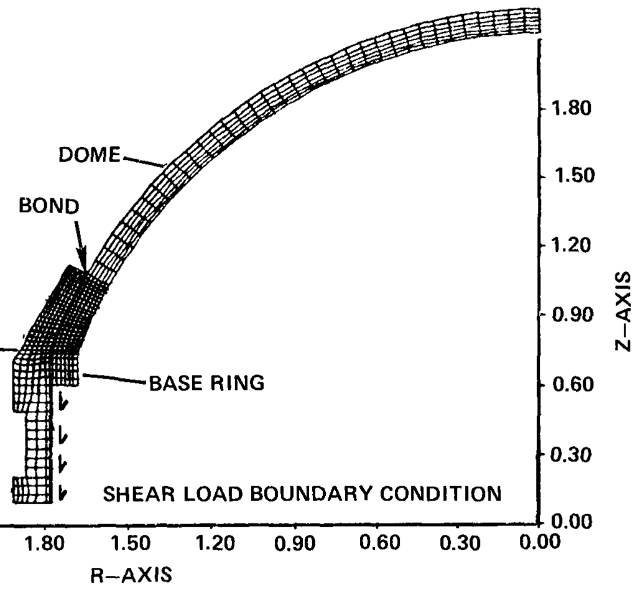

Figure 5. Dome Base Joint Finite Element Model

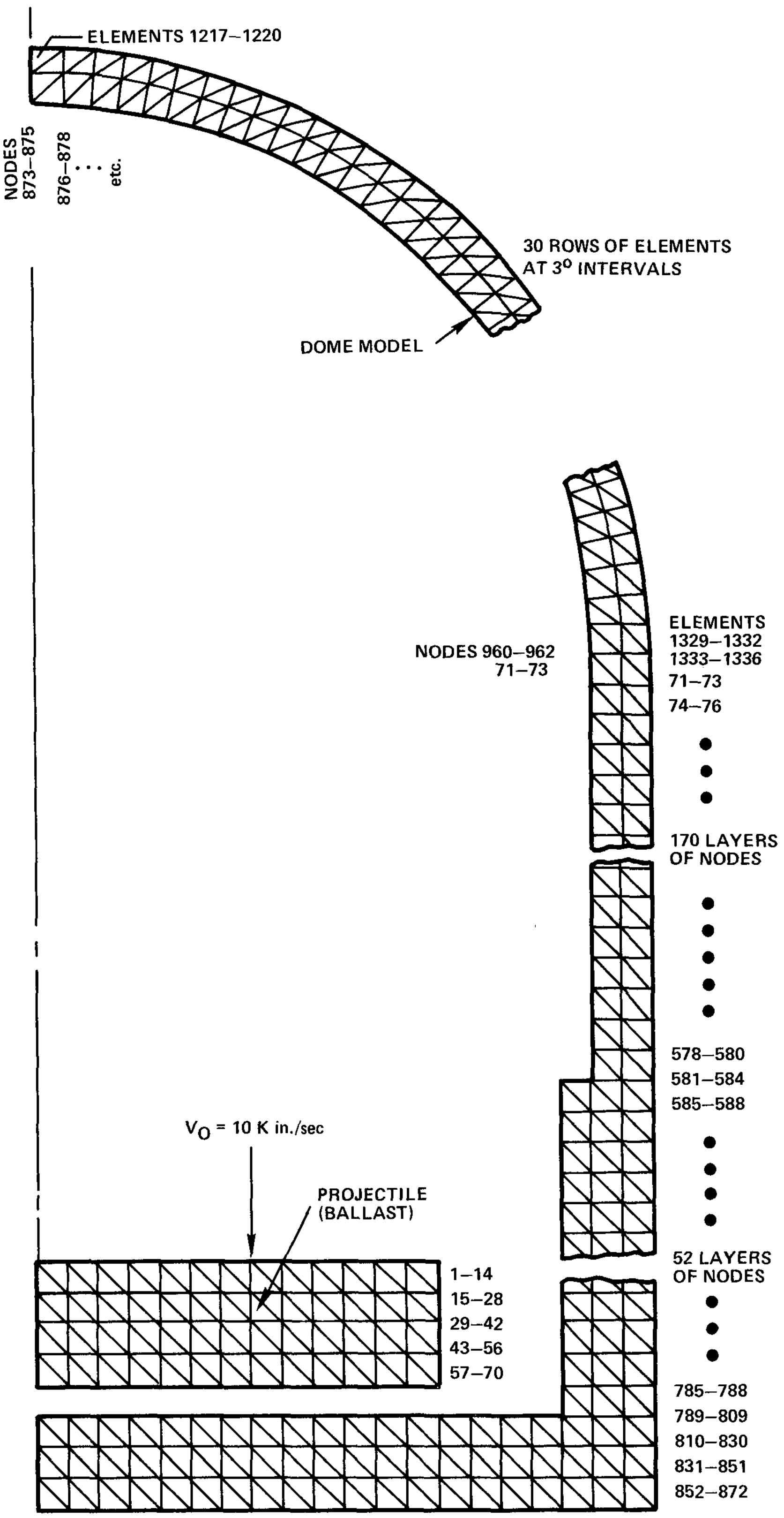

Figure 6. EPIC-2 Impact Model

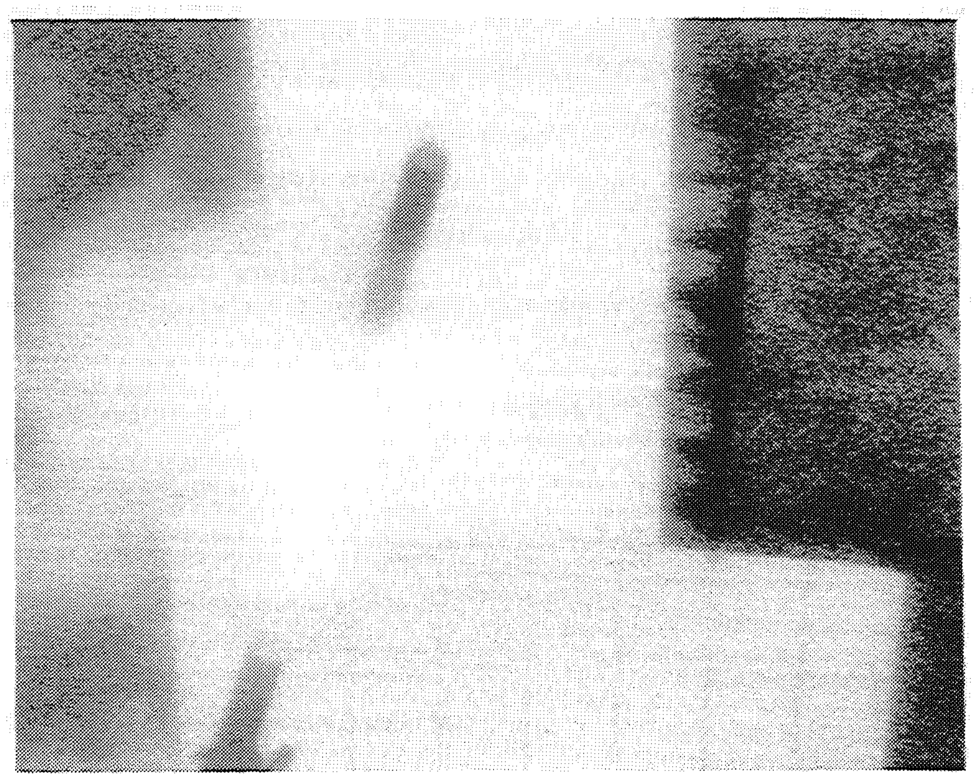

Figure 7. Projectile and Dome Immediately after Launch