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THE DESIGN OF AEROSPACE STRUCTURE BY EXPLOSIVE LOADING

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Space launch vehicle has various separation systems such as linear-shaped charge devices, severance of the structure using pyro expanding tube and pyro-actuated collet release device. This paper highlights the analysis and the testing of a pyro expanding tube type separation frame utilized in the stage separation of launch vehicles.Separation frames are made of Al7075-T651 plate material. Separation frame endure the applied structural load and easily severed by pyro expanding tube at a low level of pyroshock. Under detonation effect, a pressure shock wave is induced in the walls of pyro expanding tube. This rapid expansion of the pyro expanding tube subsequently induces a shock wave in the outer walls of separation frame. The shock wave induces sufficient stresses in the edge of separation frame due to the bending of these outer walls. This paper presents the analysis of the separation frame which sustains high structural loads and severance test of separation frames. Analysis was conducted by ANSYS and AUTODYN. Separation frames satisfy the required strength and severance performance. Pyroshock of separation frame is compared with the pyroshock of pyrotechnic devices.

Keywords: Pyro expanding tube, Separation frame, Severance test, Pyroshock, AUTODYN.

1. Introduction

Space launch vehicle has various separation systems and many pyrotechnic devices are used. Stage separation is a one of the process of launch mission. In multi-stage launch vehicle, the mission of first stage is ended; separate the first stage from the second stage for reduced the weight of launch vehicle. In order to apply pyrotechnic device to the stage separation system, structural load and pyroshock should be considered. Pyroshock is characterized by transient high acceleration and high frequencies. [Jung-Ryul Lee *et al.*, 2012] They can cause the failure of electronic components and structure of launch vehicle. [Ares J. rosakis, and G. ravichandran, 2000]

Mainly the pyro expanding tube and linear shape charge are used in stage separation system. Linear Shape Charge (LSC) device is used in large scale structure.

But debris, gas and high pyroshock happened during the stage separation. Pyro-actuated collet release device [M. Chen, *et al.*, 2007] is capable of easily installed on the structure and debris does not occur. But pyro-actuated collet release devices can with stand a low structural load and separation reliability is lower if several devices are used. Pyro expanding tube has low pyroshock and no debris compare to the LSC. Pyro expanding tube is able to withstand high structural loads and applied in the large scale structure. In this paper, severance test and analysis of separation frame using the pyro expanding tube was described. Pyroshock of severance test was compared with the pyroshock of other pyrotechnic devices.

2. Design of the Separation Frame

Figure 1 shows the pyro expanding tube of stage separation system. Pyro expanding tube has the elliptically shaped metal tube with an explosive core (MDF). Pyro expanding tube is inserted in the frame called a separation frame. The detonation is propagated along the linear explosive at a high speed, a pressure shock wave induced in metal tube. This reaction allows the elliptical metal tube to expand. This rapid expansion of the pyro expanding tube subsequently induces a shock wave in the outer walls of separation frame. The shock wave induces sufficient stresses in the edge of separation frame due to the bending of these outer walls.

In order to use the pyro expanding tube on the stage separation system, thickness of separation frame is determined and that endures the applied structure load. To confirm the performance of pyro expanding tube, severance test accomplished with 20 gr/ft pyro expanding tube. Separation plate made of Al7075 –T651 plate material and its thickness is 6.35 mm. Separation plate has the v-notch which depth 3.85 mm. Severance thickness of separation plate is 2.5 mm. Results of severance test shows in Fig. 2. From the left side of severance plate to the right side, severance happened by expansion force of pyro expanding tube. The severance thickness is 2.5 mm, but the severance length is about 3.5 mm – 4.0 mm.

Based on the test results of separation plate, separation frame is designed. Fig. 3 (a) shows the cross section of separation frame. Thickness of separation frame is

Fig. 1. Shape of pyro expanding tube.

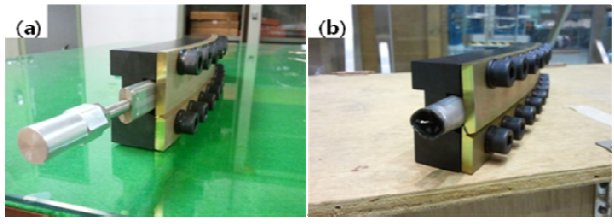

Fig. 2. (a) Expanding test of pyro expanding tube with an Aluminum plate which has the notch. (b) Results of the test.

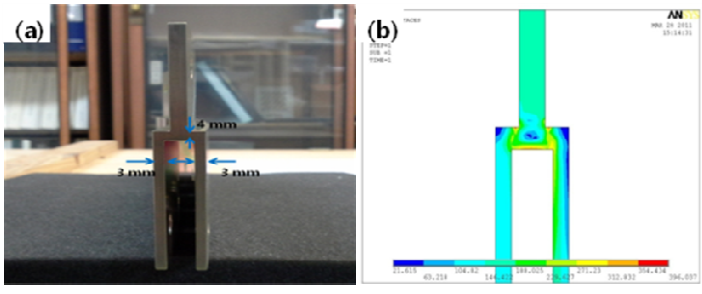

Fig. 3. (a) Shape of separation frame which made of Aluminum plate and (b) In case of 5000 kN structural load applied, structural analysis results of separation frame.

3 mm both side. Structural analysis is accomplished to confirm the strength of separation frame during the flight. FEM analysis is conducted by ANSYS and Solid 45 element is used. Bottom of separation frame is fixed and max. Equivalent load 5000 kN which expected load during the flight applied on the top of separation frame. Fig. 3(b) shows the structural analysis results of separation frame and stress of separation frame is 270 MPa. Considering the allowable stress of Al7075-T651 420 MPa, separation frame have enough safety margin about the flight load.

3. Severance test of Separation Frame

Configuration of severance test shows on Fig.4 using the separation frame which was made of Al7075-T651 and 20 gr/ft pyro expanding tube. Fixture of severance test designed to fix the separation frame on the fixture. The detonator is fired, gas and debris is generated. To block the gas and debris, enclosure structure installed on the end of pyro expanding tube. Pyroshock was measured in the near-field of separation frame using Laser Doppler Vibrometer. [H. Himalblau *et al.*, 1995] According to the AIAA S-113-2005 Standard, [AIAA, 2005] severance test of separation frame was accomplished five times. Fig.5 (a) shows the assembly of separation frame and (b) shows the results of severance test. Separation frame was severed well by expansion of pyro expanding tube. Figure 6(a) represents the variation of acceleration in time

domain and (b) represents the SRS curve in frequency domain. Measured pyroshock is about 5,000 G (4 times) and 20,000 G (1 time) in the near-field.

Additional severance test was accomplished to compare the pyroshock of pyrotechnic device which have the same size of MDF 20 gr/ft. Figure 7(a) shows the configuration of test about the severance of the shear pin using the pyro expanding tube. The role of shear pin is to connect the frames and pyro expanding tube

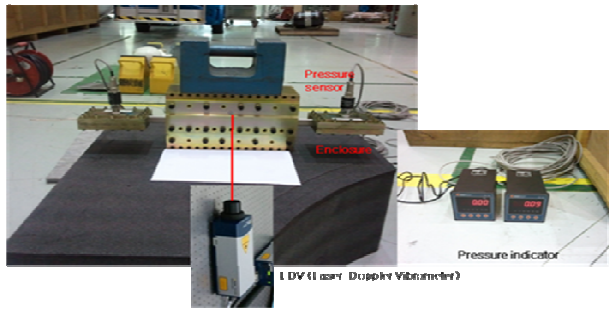

Fig. 4. Configuration of severance test and Pyroshock was measured by the LDV [S. Rothberg, *et al.*, 2000].

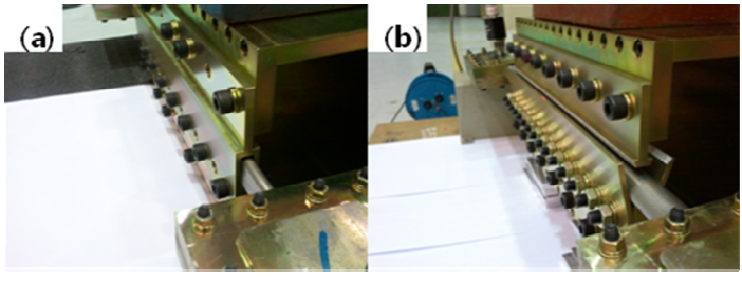

Fig. 5. Assembly structure of separation frame with a pyro expanding tube and Results of severance test.

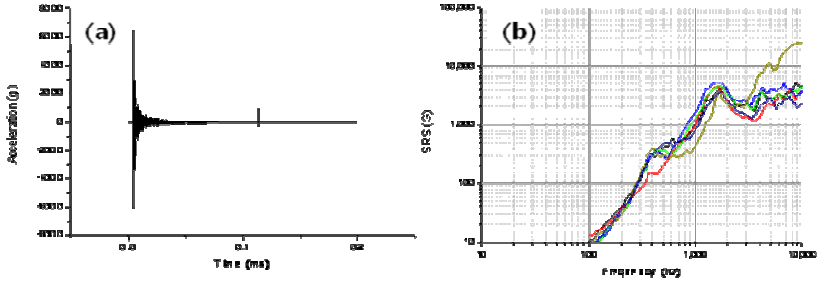

Fig. 6. From the severance test, acceleration data measured in time domain. To compare the pyroshock, acceleration data converted to the SRS data (frequency domain).

inserted between the frames. The shear pin was severed and a connected frame was separated by expansion of pyro expanding tube. Figure 7(b) shows the pyroshock of severance of shear pin test. Measured pyroshock is about 10,000 G – 20,000 G in the near-field. [Ho-Keong Jung, *et al.*, 2005] Fig. 8(a) shows the configuration of severance test using the linear shape charge device. The plate was severed by jet from the LSC partially and then perfect severance occurred by mechanical tearing of plate. Measured pyroshock is about 100,000 G in the near-field. Severance tests represent that the pyroshock which was generated by the same explosive loading was different depends on the separation method and pyrotechnic device. The pyroshock was lower in separation frame using pyro expanding tube.

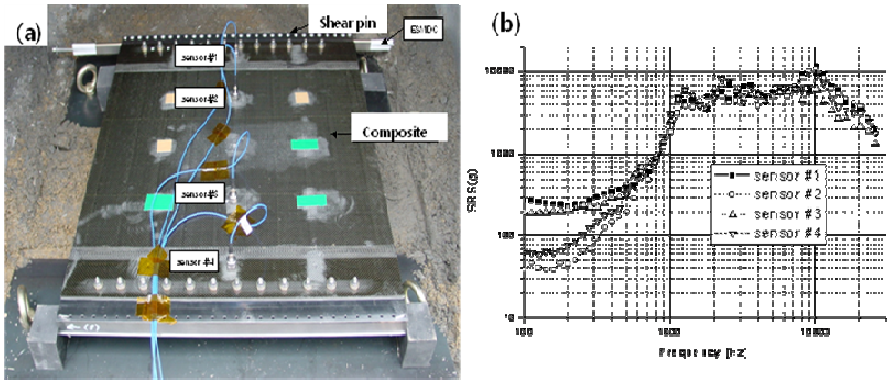

Fig. 7. Configuration of test about the severance of the shear pin using the pyro expanding tube.Max. pyroshock 10,000 G was generated in frequency domain (SRS data).

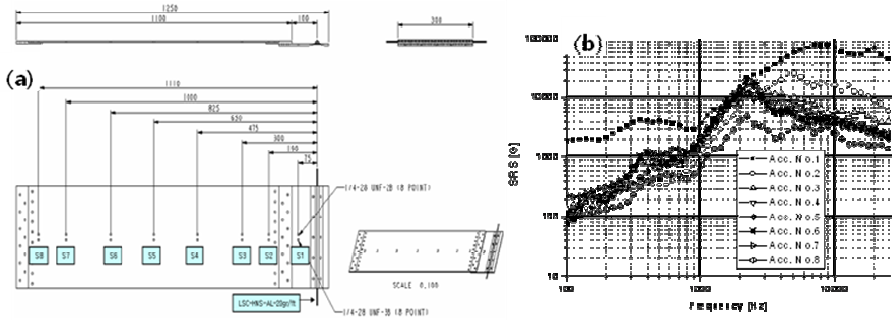

Fig. 8. Configuration of severance test using the linear shape charge device. Max. pyroshock 100,000G was generated in frequency domain (SRS data).

4. Severance Analysis of Separation Frame

Recently, numerical analysis of pyroshock effects of aerospace structure is widely accomplishing. [Y. Mao, *et al.*, 2010] Severance analysis was conducted by AUTODYN based on an explicit finite element method. Fig. 9(a) shows the severance analysis model of separation frame assembly. Severance analysis model consist of metallic tube, MDF, separation frame and the air. Fluid can be modeled using an Equation of State (EOS). The air and the explosive material HNS which inserted in MDF was modeled using the Eulerian. Metallic tube and separation frame were modeled using the shock EOS and Steinberg-Guinan strength model. Fluids and gases can be modeled using an Equation of State (EOS) that expresses the relationship between the pressure, specific volume, and specific energy. The Jones-Wilkins-Lee (JWL) and ideal gas equations were used for the EOSs of HNS and air, respectively. The JWL EOS is widely used in high-explosive detonation problems, and it is available in AUTODYN. [James Danyluk, 2010] The JWL equation, an empirical equation, is a pressure-volume relationship independent of temperature:

$$\mathrm{p} = \mathrm{A}\left(1 - \frac{w}{R_1 V}\right) e^{-R_1 V} + B\left(1 - \frac{w}{R_2 V}\right) e^{-R_2 V} + \frac{we}{V} \tag{4.1}$$

Where $A, B, R1, R2$, and w are empirically determined and depend on the kind of the explosive. The ideal gas EOS for the air is shown in Eq. (4-2):

$$p = (\gamma - 1)\rho e \tag{4.2}$$

Where γ is the ideal gas constant, and ρ and e are the density and internal energy of the air. The internal energy of air at room temperature is 2.068×10^5 kJ at ambient pressure. All of the solid parts undergoing high strain rates were modeled using the shock EOS and Steinberg-Guinan strength model. Both the von Mises yield strength (Y) and the shear modulus (G) of the Steinberg-Guinan model are assumed to be described as a function of pressure (P), density (ρ), and temperature (T), and in the case of yield strength, the effective plastic strain as well (ε):

$$\mathrm{G} = G_0\left(1 + \left(\frac{G_0'}{G_0}\right)\frac{p}{\eta^{1/3}} + \left(\frac{G_T'}{G_0}\right)(T - 300)\right) \tag{4.3}$$

$$\mathrm{Y} = Y_0\{1 + \beta(\varepsilon + \varepsilon_i)\}^n\left(1 + \left(\frac{Y_p'}{Y_0}\right)\frac{\mathrm{P}}{\eta^{1/3}} + \left(\frac{Y_T'}{Y_0}\right)(T - 300)\right) \tag{4.4}$$

Where β is the hardening constant and n is the hardening exponent. The subscript 0 refers to the reference state ($T = 300\,K, P = 0, \varepsilon = 0$). The primed parameters with the subscripts P and T indicate the derivatives of the parameters with respect to pressure or temperature at the reference state. A flow-out condition was applied to all boundaries of the Euler grid. This allowed the material to freely leave the grid, and also prevented relief waves from being generated off the lateral boundaries of the solid, which would reduce the overall strength of the compressive shock and rarefaction waves.

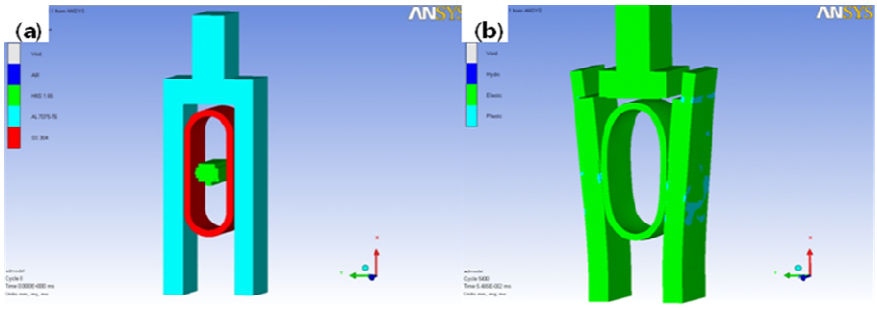

Fig. 9. (a) Severance analysis model of separation frame assembly. Analysis was conducted by AUTODYN. (b) Results of severance analysis.

A hydrodynamic failure model was used as the failure model for the separation frame. Metallic tube and separation frame use the SUS304 material and Al7075-T651 material respectively. The detonator was modeled as a point which set to the center of MDF. Energy fraction was set to 10%. Fig. 9(b) shows the results of severance analysis. Comparing the results of severance test and the results of severance analysis, the severance shape of analysis was similar to the results of severance test.

5. Conclusion

This paper describes the analysis of the separation frame which sustains high structural loads and severance test of separation frames. Also, Severance analysis was carried out. Structural and severance analysis was conducted by ANSYS and AUTODYN. It was confirmed that the separation frames satisfy the required strength and severance performance by the structural analysis and severance test (5 times). Pyroshock of separation frame is lower compared with the pyroshock of pyrotechnic devices which have the same explosive load. The results of severance analysis are compared to the results of severance test using pyro expanding tube. The results of severance analysis and severance test were well suited.

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