형상기억합금을 이용한 분리장치의 모델 및 모사에 관한 연구

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Modeling and Simulation of a Shape Memory Release Device

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ABSTRACT

Aerospace applications use pyrotechnic devices with many different functions. Functional shock, safety, overall system cost issue, and availability of new technologies, however, question the continued use of these mechanisms on aerospace applications. Release device is an important example of a task usually executed by pyrotechnic mechanisms. Many aerospace applications like satellite solar panels deployment or weather balloon separation need a release device. Several incidents, where pyrotechnic mechanisms could be responsible for spacecraft failure, have been encouraging new designs for these devices. The Frangibolt is a non explosive device which comprises a commercially available bolt and a small collar made of shape memory alloy (SMA) that replace conventional explosive bolt systems. This paper presents the modeling and simulation of Frangiblot by the change of bolt size and notch geometry. This analysis may contribute to improve the Frangibolt design.

초 록

본 논문은 기존 파이로 부품인 폭발볼트의 기능을 그대로 유지하면서 분리시 발생되는 파편 및 충격파의 악 작용과 파편을 완벽히 제거할 수 있게 형상기억합금(Shape Memory Alloy)을 이용한 분리장치(Fangibolt) 모델의 설계 및 모사에 관한 연구이다. Frangibolt는 기존 폭발볼트에서 사용하는 분리화약을 사용하지 않고 스마트 소재인 형상기억합금의 온도에 따라 변화되는 미세조직에 따른 응력생성을 이용하여 파이로 장치를 분리시키는 Non Pyrotechnic 장치로써, 실제 Frangibolt노치부에 생성되는 응력의 분포 및 분리거동을 해석함으로써 Frangibolt 설계에 필요한 인자를 파악할 수 있었다. 또한 볼트 설계방법의 최적화를 제시함으로써 향후 다른 종류의 SMA을 이용한분리장치 설계 및 해석 모델에 기초자료를 제공할 수 있을 것이다.

Key Words: Shape Memory Alloy(SMA, 형상기억합금), Release Device(분리장치), Design(설계), Simulation(모사), Frangibolt(플랜지볼트)

† 2005년 12월 29일 접수 ~ 2006년 6월 18일 심사완료

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1. Introduction

Aerospace applications use pyrotechnic devices with many different functions. Functional shock, safety, overall system cost issue, and availability of new technologies, however, question the continued use of these mechanisms on aerospace applications.

Lucy et al.[1, 2] summarizes the results of the NASA survey of non pyrotechnic alternative mechanisms. A comparison of functional shock characteristics of several devices is shown, and potentially related technology developments are highlighted.

Release device is an import example of a task usually executed by pyrotechnic mechanisms. Many aerospace applications like satellite solar panels deployment or weather balloon separation need a release device. Several incidents, where pyrotechnic mechanisms could be responsible for spacecraft failure, have been encouraging new designs for these devices.

The Clementine spacecraft, sent to space in 1994, successfully deployed its solar panels with a non explosive device, called Frangibolt. It provides a simple, safe, and inexpensive way to anchor spacecraft appendages during launch and release them on cue. Frangibolt comprises a commercially available bolt and a small collar of shape memory alloy (SMA). Frangibolt replaces conventional explosive bolt systems possessing inherent risks that range from handling and installation hazards to unintentional activation and fragmentation. Busch et al.[3] presents a discussion of Frangibolt design.

SMAs are a metal family with the ability of changing shape depending on their temperature[4]. SMAs undergo thermo elastic martensite transformations, which may be induced either by temperature or stress. When a SMA specimen is stressed at a constant temperature, inelastic deformation is observed above a critical stress. This inelastic process, however, fully recovers during the subsequent unloading. The stress strain curve, which is the macroscopic manifestation of the deformation mechanism of the martensite, forms a hysteresis loop.

At a lower temperature, some amount of strain remains after complete unloading. This residual strain may be recovered by heating the specimen. The first occasion, is the pseudo-elastic effect, while the last is the shape memory effect (SME)[5]. These effects are inter related in the sense that, if the hysteresis cycle in the pseudo elastic case is not completed when applied stress is removed, then reversion of residual martensite must be induced upon heating, by employing the SME[6]. In the process of returning to their remembered shape, the alloys can generate a large force which may be useful for actuation [7].

This paper presents the modeling and simulation of SMAs release devices by the change of bolt size and notch geometry, specially, Frangibolt. This approach may contribute to improve Frangibolt design.

2. Description of the Release Device

Release devices must be load resistant during launch and must be fractured under force generated by the actuator. Frangibolt is a simple release device using SMAs with two main components: A *notched bolt element* with matched nut and a SMA actuator (Fig. 1).

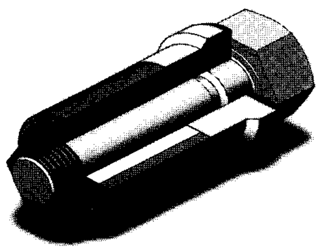


Fig. 1 Frangibolt Device

The basic idea of the device is to exploit shape memory effect to produce forces that will break the bolt, performing the release. To do it, a pre compressed SMA cylinder with an integral heater is used a actuator. By heating the actuator, SMA elongates and a force is generated.

Frangibolt has many advantages compared with pyrotechnic devices. It enables non destructive and repeated testing and greatly reduces the shock of release. The device has two potential limitations: the response time is not immediate and the phase transformation temperature cannot be much higher than phase transformation temperature cannot be much higher than 120℃. Design of Frangibolt must be alert to bolt element (bolt material, size and notch geometry), actuator element and heater[3].

3. A Constitutive Model for SMAs

Microstructural aspects of SMAs have shown that these alloys may present two possible phases: Austenite and Martensite. Martensite plates may be internally twin related. Hence, different deformation orientations of crystallographic plates constitute what is known by marsteite variants[8].

Savi & Braga[9] present an overview of some constitutive models for SMAs. Here, the model with assumes the kinetics, proposed by Tanaka[5] and co worker, is considered. It is a one dimensional model which assumes the kinetics of phase transformation establishing a relationship between the martensite fraction, β, and other internal variables such as temperature, T, and one dimensional strain, e. The rate form of constitutive equation is given by,

$$\dot{\sigma} = E\dot{\varepsilon} - \alpha\dot{\beta} - \Xi\dot{T} \tag{1}$$

where E is the elastic modulus, Ξ is a thermodynamic coefficient and α is a coefficient associated with phase transformation. They are positive constants. The martensitic fraction β can assume a value in the range $-1 \le \beta \le +1$. $\beta = +1$ means that the body is 100% on a martensitic variant M+, which is induced by tensile stresses. $\beta = -1$, by the other side, means that the body is 100% on a martensite variant M-, which is induced by compressive stresses. $\beta = 0$ is associated with the matrix phase, which may be austenite or twinned martensite, depending on temperature.

Phase transformation is assumed to be determined by the current values of stress and temperature, $\beta = \beta(\sigma, T)$. The transformation from austenite to martensite may be described by an exponential law:

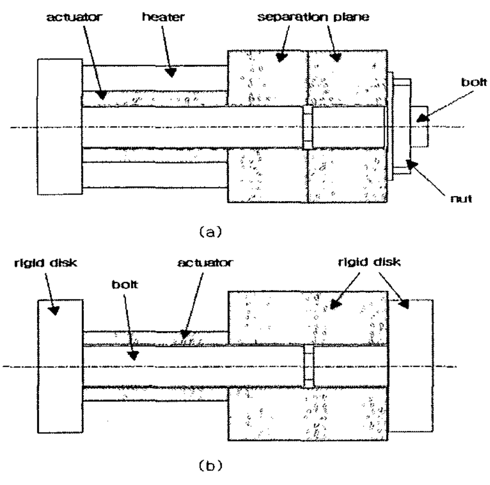
$$\beta = \{1 - \exp[-a_M(M_S - T) - b_M|\sigma|]\}sign(\sigma) \tag{2}$$

where $sign(\sigma)=\sigma/|\sigma|$. a_M and b_M are positive constants. M_S is the temperature at which martensite phase begins to be transformed. This equation holds for, $\sigma \ge (a_M/b_M)(T-T_M)$.

The reverse transformation is described by another exponential law,

$$\beta=\{\beta^M \exp[-a_A(T-T_S)+b_A|\sigma|]\}sign(\sigma) \quad (3)$$

where a_A and b_A are positive constants and β^M represents the volumetric fraction of martensite when the reverse transformation begins to take place. A_S is the temperature at which austenitic phase begins to be transformed. This equation holds for, $\sigma \ge (a_A/b_A)(T-T_A)$.



(a) Device (b) Model

Fig. 2 Scheme of Frangibolt Release Device

4. Modeling of the Release Device

Frangibolt modeling proposed here considers that all components, except SMA actuator and bolt, are rigid. Fig. 2 shows device and modeling schematic diagrams.

By heating the pre compressed SMA actuator, it elongates causing the bolt deformation. The rate form of displacement on each element is given by ;

$$\dot{U}_B=\frac{\dot{P}}{K_B} \quad (4a)$$

$$\dot{U}_S=\dot{\varepsilon}_S L_S \frac{L_S}{E_S}(\dot{\sigma}_S+\alpha\dot{\beta}+\Xi\dot{T}) \quad (4b)$$

Where P and K_B is the force and stiffness of the bolt, respectively. L_S is the actuator length. For the geometry adopted, finite element simulation of the notched bolt shows that a linear relationship between force and displacement can be assumed without any loss in the elastic region[3]. By compatibility requirements,

$$\dot{U}_B=\dot{U}_S \quad (5)$$

By considering the force P that acts on both elements, equilibrium establishes that,

$$\sigma_S=-\frac{P}{A_S} \quad (6a)$$

$$\sigma_B=\frac{P}{A_B} \quad (6b)$$

Hence, it is possible to write,

$$\dot{\sigma}_S = -K\alpha\dot{\beta} + \Xi\dot{T} \tag{7}$$

where, $K = \dfrac{1}{1+(K_S/K_B)}$ and $K_S = \dfrac{E_S A_S}{L_S}$ is the linear elastic axial stiffness of the actuator.

For austenite martensite transformation, the following evolution equation is obtained using relation (2) in equation (7):

$$\dot{\sigma}_S = K\frac{[\alpha a_M(1-\beta)-\Xi\dot{T}]}{[1+K\alpha b_M(1-\beta)sign(\alpha)]}\dot{T} \quad for\ |\sigma| \geq \sigma_M \tag{8}$$

For the reverse transformation, using relation (3) in equation (7), it is obtained,

$$\dot{\sigma}_S = K\frac{[\alpha a_A\beta-\Xi\dot{T}]}{[1+K\alpha b_A\beta sign(\alpha)]}\dot{T} \quad for\ |\sigma| \leq \sigma_M \tag{9}$$

An iterative predictor corrector numerical procedure is used to solve the governing equations. The procedure considers a thermo elastic predictor step where no transformation takes place, that is, $\dot{\beta} = 0$. Next, an iterative integration scheme is used to obtain σ_S and β. The process must be repeated until convergence is achieved.

5. Numerical Simulations

A working device that has been successfully tested in space[1] is chosen in the numerical simulations. This device has a Nitinol actuator with 25 mm length, 6.6 mm inside diameter and 12.7 mm outside diameter.
Titanium 318 bolts with a 1/4 inch and 1/2 inch diameters with 60 and 63 mm length are considered respectively. The 1/4 inch bolt has 1.11, 1.0 and 0.8 mm deep notch with 0.25 mm radius and the 1/2 inch bolt has 2.0, 1.5 and 1.0 mm deep notch with 0.25 mm radius. The thickness of bolt head in 1/4 and 1/2 inch is 5 and 8 mm respectively.

The actuator is pre compressed and, as a consequence, a 2.5% residual strain is obtained. It guarantees 100% of martensite phases (M). A heater with a silicon rubber insulation and adhered to Nitinol cylinder furnishes 120KW/㎡, which is sufficient to promote a temperature rise of 100℃, Material parameters are presented in Table 1 (Jackson et al)[10] and Table 2 (Smithells) [11].

Table 1. Material Parameters. Nitinol SMA Actuator

Es (Gpa)	α (Gpa)	Ξ (Kpa)	Ms (℃)	As. (℃)
60	1.25	6.42	20	50
A_M (℃$^{-1}$)	b_M (Mpa^{-1})	a_A (℃$^{-1}$)	b_A (Mpa^{-1})	
1,100	0.08	1,100	0.080	

Es : elastic modulus

α : a coefficient associated with phase transformation

Ξ : A thermodynamic coefficient

Ms : the temperature at which martensite phase begins to be transformed

As: the temperature at which austenite phase begins to be transformed

A_M and b_M are positive constants

a_A and b_A are positive constants

Table 2. Material Parameters, Titanium Bolt

Young Modulus (Gpa)	Yield Stress (Gpa)	Tensile Stress (Gpa)	Rupture Elongation (%)
106	1.05	1.15	4.0

Modeling is working at Patran 2005 and ABAQUS 6.5 is used on finite element simulations to determine bolt response. By considering an elastic analysis, a linear relationship between force and displacement is observed for all stresses studied. Indeed, a constant stiffness of 63 GN/m is adopted in the following analysis[12].

Figure 3 shows the modeling of shape and the finite element method in Frangibolt. Creating a model of shape is used Patran 2005R2 and whole assembly is made from a model of individual item. Fig. 3 also appears the assembly cutting a half to the parallel direction.

First, load resistance during launch is analyzed by considering a force P=5KN applied to the bolt (Busch et al.)[3]. The result shows axial strain over the bolt length. Strains are concentrated near the notch as it was expected. It is also shown Von Mises equivalent stresses in the bolt notch region. In a small region, the stress almost reaches the yielding limit (σ_Y). Stress concentration factor near 3 is observed.

Now, by heating SMA actuator, release procedure is simulated. The result from the observation of Savi is shown force displacement

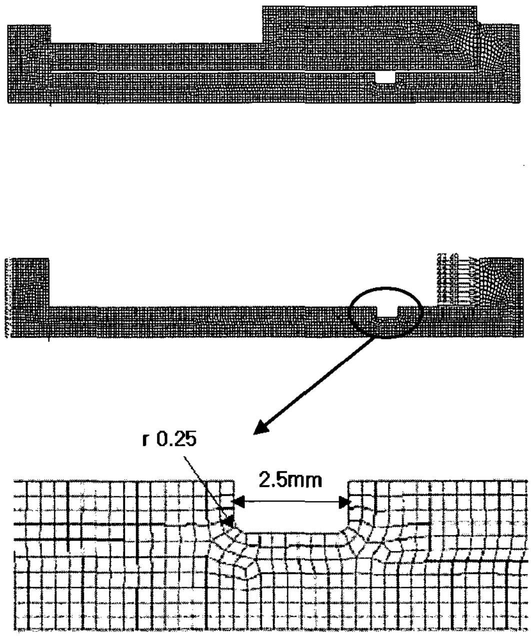
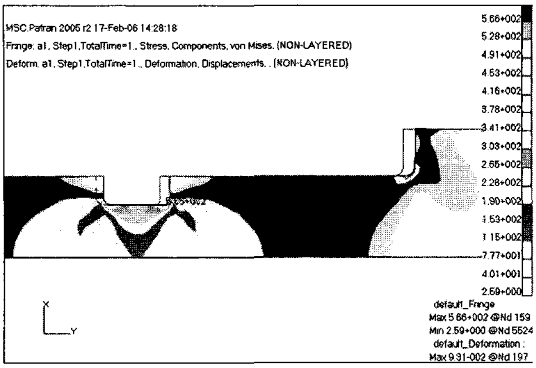


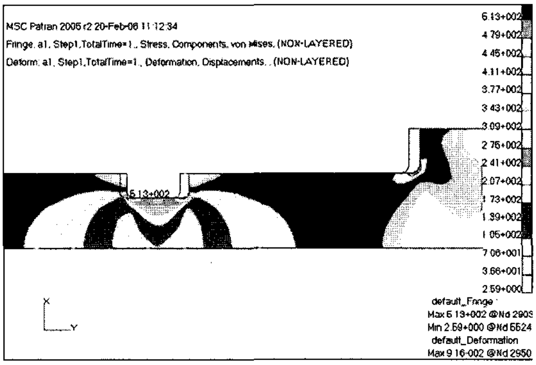
Fig. 3 Finite Element Method in Device

and martensite fraction evolution with temperature variation. It shows that martensite phase is completely transformed to austenite phase from 80℃ and then load is approximately 32 KN at 80℃[12]. Phase transformations induce actuator strain recovery which promotes the release by loading the notched bolt until it breaks.

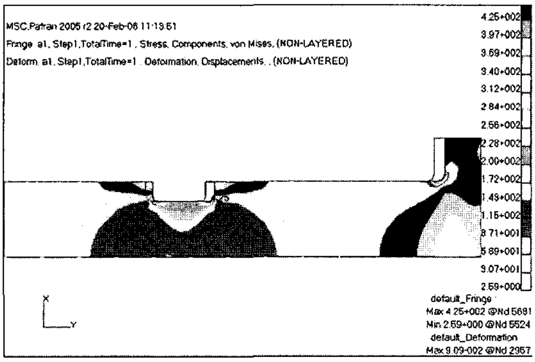
Figure 4 show stresses over the 1/4 inch bolt only by considering a force P = 5 KN. It shows that the bolts with 0.8 and 1.0 mm notch depth were stressed the corner of bolt head. Therefore, the bolt with 1.1 mm notch depth is suitable to design. Fig. 5 show stress over the 1/2 inch bolt by force P = 5 KN. It is similar to that of 1/4 inch bolt. The bolts 1.5 and 1.0 mm notch depth are stressed the edges of the bolt head compare to the 2.0 mm notch depth.



(a) 1.1 mm

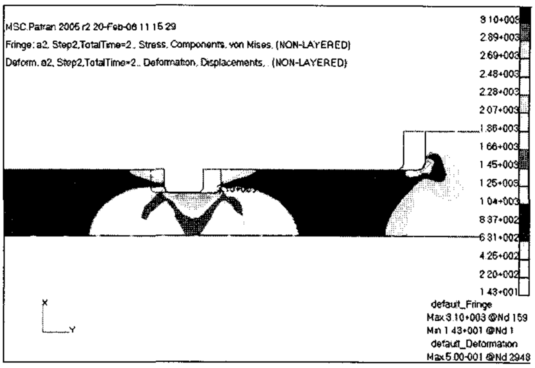


(b) 1.0 mm

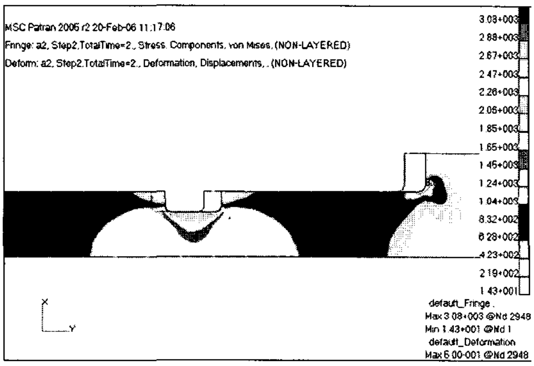


(c) 0.8 mm

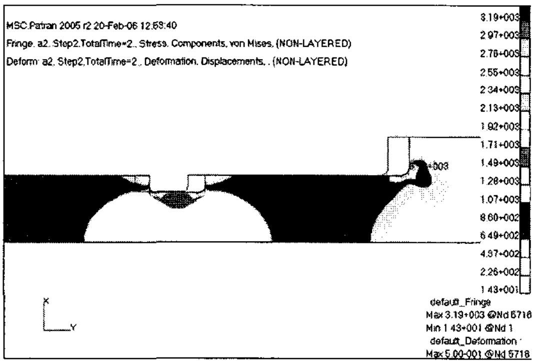
Fig. 4 The Distribution of Pressure Changing Notch Depth under the Pre load in 1/4 inch Bolt



(a) 2.0 mm



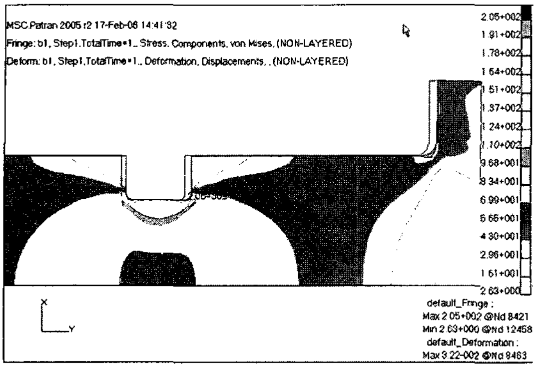
(b) 1.5 mm



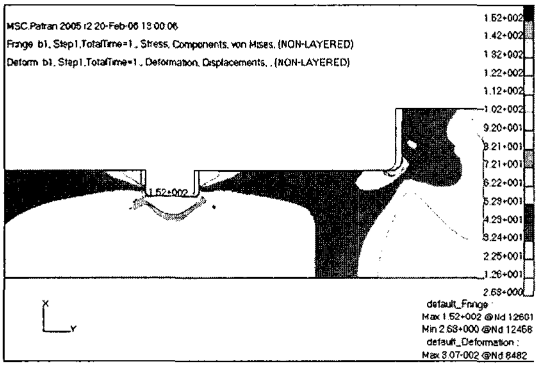
(c) 1.0 mm

Fig. 5 The Distribution of Pressure Changing Notch Depth under the Pre load in 1/2 inch Bolt

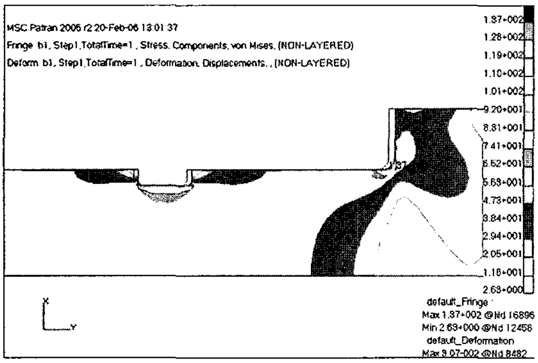
By considering the maximum force produced by the actuator, it is possible to analyze bolt response on release procedure. Figures 6 and 7 show stress over the 1/4 inch and 1/2 inch bolt with notch depth for P = 32 KN, respectively. An elastic finite element analysis



(a) 1.1 mm

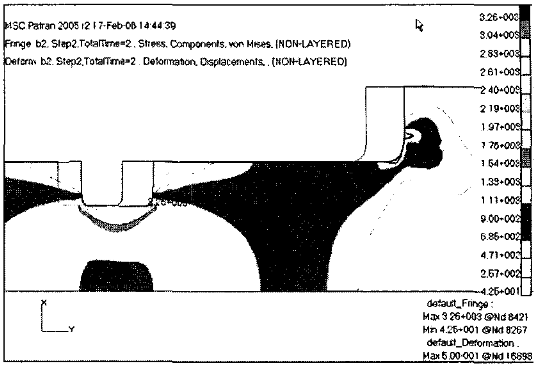


(b) 1.0 mm

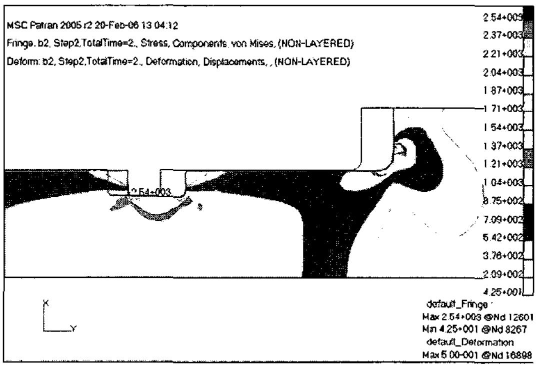


(c) 0.8 mm

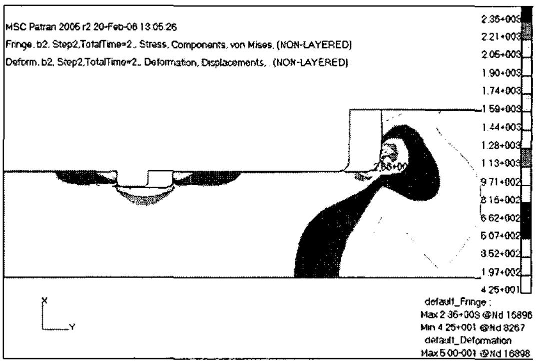
Fig. 6 The Distribution of Pressure Changing Notch Depth under the Full load in 1/4 inch Bolt



(a) 2.0 mm



(b) 1.5 mm



(c) 1.0 mm

Fig. 7 The Distribution of Pressure Changing Notch Depth under the Full load in 1/2 inch Bolt

is developed and maximum values of 3.1, 3.08 and 3.19 Gpa with 1.1, 1.0 and 0.8 mm notch depth and 5 % with, respectively, are observed at the notch. The 1/2 inch bolt case, maximum values of 3.26, 2.54 and 2.36 with 2.0, 1.5 and 1.0 mm notch depth are acted at the notch. The results show that the 1/4 inch bolts with 1.0 and 0.8 mm notch depth are changed the corner of bolt head or are strengthened, and the 1/2 inch bolt with 1.5 and 1.0 mm notch depth are also changed and redesigned the edges of bolt head. The maximum stress from the present analysis in 1/4 and 1/2 inch bolt is illustrated to Table 3. It informs from the present analysis that the SMA actuator is sufficient to break both 1/4 inch and 1/2 inch bolt. Actually, the bolt experiments plastic deformations, but the elastic analysis furnishes a simple and conservative way to simulate the device behavior. An elasto plastic analysis will predict lower stresses and higher strains.

Table 3. Comparison of Maximum Stress in 1/4 and 1/2 inch Bolt

Size	1/4 inch			1/2 inch		
Notch Depth (mm)	1.1	1.0	0.8	2.0	1.5	1.0
Max. Stress (Gpa)	3.1	3.08	3.19	3.26	2.54	2.36

6. Conclusions

Release device is an import example of a task usually executed by pyrotechnic mechanisms. Many aerospace applications like satellite solar panels deployment of weather balloon separation need a release device. Several incidents, where pyrotechnic mechanisms could be responsible for spacecraft failure, have been encouraging new designs for these devices. This work presents the modeling and simulation of release devices using SMAs, specially, Frangibolt. It informs from the present analysis that the SMA actuator is sufficient to break both 1/4 inch and 1/2 inch bolt. Despite the simplicity of the model proposed, it predicts results which are consistent with experimental requires. This analysis may contribute to improve Frangibolt design. The proposed model can be improved by considering an elasto plastic analysis.

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