Design and Analysis of Release Mechanism using Shape Memory Alloy for Spacecraft

Shrutika Dahake¹,*, Nilesh Awate², Rupesh Shelke²

¹PG Scholar, Department of Mechanical engineering, G H Raisoni Collage of Engineering Nagpur, India
²Professor, Department of Mechanical Engineering, G H Raisoni Collage of Engineering Nagpur, India

shrutikadahake6@gmail.com¹,*, nilesh.awate@raisoni.net², rupesh.shelke@raisoni.net²

Abstract: Shape memory alloy (SMA) is used as a smart material. It is also called as Nitinol and intelligent material because it regains their original shape after deformation. It works on the principle of shape memory effect which regain their original shape after passing through different temperature phases. SMA get some more attention in incoming years due to their superior and unique properties. This paper presents design and maximum stress analysis of release mechanism using SMA. It also covers the capability and efficiency of notch bolt of Frangibolt mechanism. Its design, calculation and analysis has done in CAD software and simulation software.

Keywords. Shape Memory Alloys, Nitinol, Frangibolt, Release Mechanism.

1. Introduction
During the launch of a space vehicle, Antenna and solar panels are initially folded to reduce its size. Once the spacecraft reaches its orbit, it needs to be deployed to perform its function. Design constraints viz. simple, compact in size, lightweight, low shock, reusable and easy to reset have been considered while designing the Release Mechanism.

Release mechanism is actuated by using Shape Memory Alloy (SMA) which works on the Shape Memory Effect (SME) i.e., When SMA wire is heated above its transformation temperature, it will transform from Martensite phase to Austenite phase. i.e. it will regain its parent shape. This release mechanism can be used for the deployment of solar arrays and antennas of small size satellites. Shape memory alloy (SMA) having some native properties, specially regain its original form by increasing or decreasing temperature. In 1938 Mooradian and Greninger observe the shape memory effect for (Cu-Sn). In 1961 Buehler and Wiley invented a Nickel-Titanium alloy called NiTi-NOL[1]. In Nitinol Ni contain 55 wt% and the rest is Ti[2].

2. Aerospace applications
In 1960s, Raychem developed Cryofit connectors for F-14 airplane hydraulic circuit. It is the first industrial SMA applications in aeronautics.[1]. Because of unique properties of SMA, it has huge
application in aerospace such as actuators [3], sealer, release or deployment mechanism, vibration dumper, manipulators and the pathfinder applications and structural connectors [1].

In spacecraft, SMAs used as low shock release mechanism. Best example is CryoFit. CryoFit in which coupling is made from SMA material. Applications of CryoFit are such as tubes used in aircraft, hydraulic lines, and fuel lines. When these tubes are broken, they often have to be repaired by people working in confined conditions. In this situation, it is very difficult to use welding and brazing because these processes require bulky equipment. Hence, CryoFit coupling is used. Because they release slowly with minimum vibration. CryoFit and Frangibolt [4] are some example of small device which shape memory alloys material is used.

3. Types of Hold Down release Mechanism (HDRM)

There are two basic types of hold down release mechanism, Pyrotechnic HDRM (Explosive HDRM) and Non-Pyrotechnic HDRM (Non-Explosive HDRM).

3.1. Pyrotechnic HDRM.

In this pyrotechnic HDRM, shaft is made inside of the bolt that specifically made to break at certain location along its length as shown in the fig.1 [4]. This location typically has a smaller diameter than the rest of the bolt inside the shaft. A low sensitivity and high density explode taking place on the top of that small amount of low-density. If this is placed finally, the filament bridge wire initiator is placed above the low-density where it’s at time to separate the parts that are held together by the bolt and illogical current is passed through a pyramid inside the initiator. It heats up quickly and the ignites small amount of pyrotechnic powder. The Powder burns rapidly creating lots of gas at high temperature and pressure. This causes the low-density explosive to detonate. These detonations create a shock wave and then the final explosion inside of the bolt causes the part of the bolt that has a smaller diameter to fill first because it’s the weakest part of the bolt. The bolt breaks apart cleanly causing the two parts to separate.

![Fig.1 Pyrotechnic HDRM](image)

This sequence of events is overly complicated and may wonder why the high-density explosive is not connected directly. The main reasons are safety, reliability and accuracy. The high-density explosive is made less sensitive to prevent it from exploding due to force encountered during the mission because of this small explosive is required to trigger it. This comes from the low density is used to trigger the expressive and exploding bridge wire is used because it can reliably detonate the low-density explosive accurately in a certain amount of the time after activation. This timing is important during deployment
because the one second delay means that a spacecraft will be many km away from where an event was to be triggered. Another configuration for the pyrotechnic hold down release mechanism is one where the expanding gas generated by the explosive is used to push to hemisphere of threaded coupling apart. These will lose the bolt that screwed into the coupling. A compressed spring can pull the parts away. pyrotechnic HDRM suffers from one measure issue. The detonation of exclusive produce shockwaves when they are triggered. This shockwave is transmitted throughout the spacecraft and can potentially damage electronic circuit boards optical device alignment and other sensitive component. For reducing this shockwave was one of the reasons for the deployment of a second type of HDRM.

3.2. Non pyrotechnic HDRM
Non pyrotechnic HDRM is the split spool initiator. In this design a groove has curved into the middle of cylinder as shown in fig. 2A. the cylinder is split in half lengthwise but is then held together by wrapping a tensile wire around it one end of this wire is fixed to the frame of the HDRM and the other end is hooked to linked wire inside the groove of the cylinder is the pleasure pin which is being pressed into the groove by spring loaded attachment inside, this attachment is threaded coupling to which the voges attached as shown in fig 2. This coupling is also split lengthwise but held together by protrusions inside of the attachment to trigger this HDRM and release the bolt a high current is passed through the linked wire this causes is to vaporise and release one end of the tensile wire. Now with the only one side held down tensile wire unwind and is unable to hold it to hemispheres of the cylinder together under pressure from the spring. the attachment along the plunger pin is now pushed forward, now that the cylinder is no longer blocking the movement of the plunger pin as a consequence of the attachment moving forward, the protrusions that kept the two halves of the threaded coupling to heater are now moved forward. This Dennett result in the two halves of the coupling moving apart and releasing the bolt just like with the pyrotechnic design. The apparent complexity of this design is related to safety and reliability.

![A. Before Actuation  B. After Actuation](image)

**Fig.2 Non- Pyrotechnic HDRM**

since this design does not contain any chemical reaction. The delay from trigger to release is more consistent. The rest of the mechanism is there to redirect the energy of the spring to make the connection between the bolt and coupling fail cleanly as spacecraft become bigger and more complicated innovative ways of folding a space craft of fate inside a rocket are being created.

So, while holding release mechanisms do not take about frequency when it comes to spacecraft systems. Hence non-pyrotechnic HDRM is always better option than pyrotechnic HDRM. SMA based and paraffin-based mechanism are the two types of non-pyrotechnic HDRM.
4. **Functional requirement of release mechanism in today’s era**
   - It should be of non-pyrotechnic type
   - Capable of moderate preload
   - Design should be simple, compact lightweight in construction
   - In flight model Capable of functional testing
   - Less shock than explosive devices
   - Easy to reset

5. **Comparison Between Pyrotechnic and Non-pyrotechnic HDRM**

| Name of parameter       | Pyrotechnic HDRM | Non-pyrotechnic HDRM |
|-------------------------|------------------|-----------------------|
|                         | Pyrocutter       | SMA Based             | Parafin based         |
| 1. Source shock generation | Very High (20000 to 6000g) | Low (4000 g to 0g)   | Low (100 g to 0g)    |
| 2. Preload Capacity     | Very High        | High                  | High                  |
| 3. Power Requirement    | Low              | Low                   | High                  |
| 4. Out gassing          | Moderate to Ni   | Nil                   | Nil                   |
| 5. Time of actuation (min-sec) | Low             | Low                   | High                  |

In the present study the SMA have been extensively used and lot of developmental activities is in progress. In this paper we are going to discuss on SMA based release mechanism.

6. **SMA Based mechanisms**

Shape Memory Alloy (SMA) works on the principle of shape memory effect (SME). In SME previously deformed alloy can be made to recover its original shape simply by heating. When the alloy is stressed and it returns to the original shape without heating then it is called Super Elasticity (SE). Material is in the austenite phase at high temperature and in the martensite phase at low temperature. When a material is cooled it changes phase from austenite to martensite, but this martensite is in the form of twinned martensite. When a material is loaded the material gets deformed and its form changes from twinned martensite to de-twinned martensite. The maximum deformation is limited to 8%. When heat is applied SMA recovers its original form. Martensite is converted back to austenite by heating. Fig. 3 shows a stress-strain curve of it. [4] Some of the examples of the SMA alloys are Ni-Ti, Ti-Nb, Ti-Nb-Sn, Ti-Nb-Al, Ti-Nb-Ta, Ti-Nb-Pt, Cu–Al–Be, Cu–Zn–Al, etc. [4] Frngibolt and Pin-puller are the example of SMA based hold down release mechanism.

![Stress-strain curves](image)

Fig.3.: Stress-strain curves [1]

A. Shape memory effect    
B. Super elasticity
6.1. One way shape memory effect (OWSME)
During heating the shape changes, this transformation is called the one-way shape memory effect. OWSME deliver more economical solution. Diverse training method was proposed [2] such as spontaneous and load assisted induction.

6.2. Two way shape memory effect (TWSME)
SMA’s ability to recover a native shape when heated, and then return to an alternative shape when cooled down its transformation temperature is called as two-way shape memory. Mild heating in two-way systems destroys SME. Two-way SMAs are a more dynamic mechanism than SMAs used in one-way systems.

6.3. Super thermo elastic effect
The basic behavior is the same as in the case of TWSME: some of the mechanical and physical properties belongs between thermal conductivity, young’s modulus, thermal expansion and electrical resistivity [5]

7. Frangibolt
The Frangibolt is a simple release device consists of four major component groups. (A) Notched bolt element and matched nut (B) SMA actuator (C)Heater and insulation (D) Joint materials and other hardware. The basic idea of the frangibolt is to utilize shape memory effect to generate forces that will break the notch bolt. When a current is applied through the heater, the SMA cylinder elongates and fractures the bolt element, in this way the separation of two or elements takes place.

7.1. Bolt element
- Design of bolt element of frangibolt [6]

Diameter= 6.35mm
Length= 50mm
1.11mm deep notch with 0.25 radius

![Fig.4 CAD Model of bolt](image)

Material Selection
Titanium 318 (6Al- 4V) material is selected because it possesses good fatigue properties with corrosion resistance, great strain recovery beyond its ultimate tensile limit.
Table 1: Properties of the Titanium used in the Ansys model [7-8]

| Name of property          | Value                |
|---------------------------|----------------------|
| Density                   | 4429 kg/m$^3$        |
| Coefficient of thermal expansion | 8.789e-5 C$^{-1}$   |
| Young’s Modulus           | 1.11e11 Pa           |
| Poisson’s ratio           | 0.3387               |
| Bulk Modulus              | 1.074e11 Pa          |
| Shear Modulus             | 3.713e10 Pa          |
| Ultimate tensile strength | 985-1090 MPa[7]      |
| Elastic Modulus           | 106 GPa              |
| Rapture elongation        | 4.2%                 |

7.2. SMA Actuator

- Design of SMA actuator of frangibolt

Length = 25mm
Inside diameter = 6.6mm
Outside diameter = 12.7mm

![Fig. 5 CAD model of actuator](image)

- Material Selection

Shape memory alloy material is selected because it generates larger strain recoveries and higher forces as compare to other material and it maturely manufactured to meet aerospace specification. SMA can produce as much as 400 MPa.

Table 2: Properties of the SMA used in the Ansys model [6, 9-10]

| Name of property                      | Value          |
|---------------------------------------|----------------|
| Hardening Parameter = 85MPa          | 85MPa [9]      |
| Reference Temperature = 296K         | 296K [9]       |
| Elastic Limit                         | 192MPa [10]    |
| Temperature Scaling Parameter         | 5.6 [10]       |
| Maximum Transformation Strain         | 0.04           |
| Martensite Modulus                   | 60000MPa       |
| Thermal Conductivity                  | 18 W/m$^0$ºC   |
| Young Modulus                         | 90000 MPa [6]  |
| Phase transformation coefficient      | 1.25 Pa        |
7.3. Design of joint material and other hardware
Nut, washer is designed as requirement of bolt and all this material made up by SS-304

Fig. 6 CAD model of nut            Fig. 7 CAD model of washer

SS-304 material is already preloaded in Ansys 2020R2

Table 3: Properties of the SS-304 used in the Ansys model

| Name of property    | Value       |
|---------------------|-------------|
| Density             | 7850 kgm\(^{-3}\) |
| Young Modulus       | 2E+11 Pa    |
| Poissons ratio      | 0.3         |
| Tensile yield strength | 2.5E+08 Pa |

7.4. Assembly

Fig. 8 CAD model of assembly of frangibolt

7.5. Analysis
Titanium Bolt preload gives benefits the operation of actuator. By rising preload value, the SMA actuator stroke wanted to break the bolt. So firstly, we have to calculate notch capacity of bolt, because notch play very important role in frangibolt device. According to this we can calculate how much maximum force can sustain a bolt.
7.6. **Finite Element Model**

![Meshing model using Ansys Workbench](image)

Tetrahedron meshed was used for discretization. Average quality of element was found to be 0.86945. The number of elements used for analysis is approximately 150,000.

7.7. **Boundary Condition**

![Fixed support](image) ![Pulling Force](image)

The head of nut is fixed. Fixed constraints are as shown in Fig. 10, and pull force applied on another end shown in Fig. 11.

7.8. **Forces**

Equivalent stresses are determined using structural analysis:

- a. $P=8\text{ KN}$
- b. $P=10\text{ K}$
- c. $P=12\text{ KN}$
- d. $P=15\text{ KN}$
- e. $P=16\text{ KN}$
- f. $P=17\text{ KN}$
After analysis we can consider that minimum 17 KN force gives is required to break the notch

7.9. Force on Assembly
After applying 17 KN force on assembly it generates 1108.4 Mpa equivalent stress. The SMA actuator produce more force than this, then only release mechanism will work. So, we can conclude that 17 KN minimum load required for release mechanism

7.10. Effect of applying various load on bolt
Fig.13 shows that effect of applying various load on bolt

8. Conclusions
During the analysis, the value of minimum force required to break the notch of bolt element is recorded. A non-explosive release mechanism is designed and tested. The release of a notch bolt is done by SMA wire. SMA wire works the principle of the Shape Memory Effect (SME). When SMA material is loaded it gets deformed. When it is heated it regains its original parent shape. This will generate force, which is used for the actuation of the release mechanism. The testing of the release mechanism is done. Test shows that it will sustain a preload of P =17 KN. In the future, higher preload capacity, quick release, low shock, lightweight, higher reliability release devices can be designed. This analysis will give major role to contribution of improving frangibolt design.
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