AiMT

Advances in Military Technology
Vol. 14, No. 2 (**2019**), pp. 231-243
ISSN 1802-2308, eISSN 2533-4123
DOI 10.3849/aimt.01283

Cartridge Case Design and its Analysis by Bilinear, Kinematic Hardening Model

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The manuscript was received on 8 December 2018 and was accepted after revision for publication on 7 July 2019.

Abstract:

The objective of this research paper is to design the cartridge case and to carry out its analysis by bilinear, kinematic hardening model for water disruptor applications. An attempt has been made in the paper to determine the strain of the cartridge case theoretically and experimentally by conducting tensile testing of test specimen. The maximum strain experienced by the cartridge case is calculated as 0.395×10^{-3} $(\varepsilon_{\text{return}})$*using bilinear kinematic hardening model. The aim of this paper is to provide theoretical calculations and technological aspects about the study of bilinear kinematic hardening model of power cartridge. After the conducting of the trials, it was ensured that smooth extractions of cartridges were observed.*

Keywords:

bilinear, breech module, kinematic hardening, improvised explosive devices, modulus of elasticity, obturation, power cartridge, stress, strain, water disruptor

1. Introduction

The role of cartridge case in any ammunition is vital, as it provides the obturation. Further, it contributes to holding the propellant with initiation system. The material of construction for cartridge case is generally brass. The cartridge cases are confined space, in which propellant combustion takes place, quickly to generate gases at high temperature and pressure, for performing mechanical tasks [1]. Therefore, they are also called gas generators. In all military aircraft, these cartridges are utilized to operate various systems and sub-systems. One of the vital applications is to save the life of aeronaut from the disabled aircraft in the shortest possible time. Apart from these applications, another important application of such cartridges is destruction of dangerous improvised explosive devices (IEDs), by generating

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Nomenclature

E_{case}	Modulus of elasticity of case, [GPa]	U_{case}	Radial Expansion of case, [mm]
$E_{case\text{-}tangent}$	Tangent modulus of cartridge case material, [GPa]	U_{PC}	Radial Expansion of pressure chamber, [mm]
E_{tube}	Modulus of elasticity of tube, [GPa]	$U_{residual}$	Permanent radial displacement of the case, [mm]
P_e	External pressure in the chamber, [MPa]	Y	Yield value of the material, [MPa]
P_i	Internal pressure in the chamber, [MPa]	ε	Strain developed in the case
R_i	Inner radius of chamber, [mm]	υ	Poisson's ratio
R_o	Outer radius of chamber, [mm]	σ	Hoop stress developed in the case, [MPa]
r_{case}	Outside radius of the case, [mm]	σ_{max}	Maximum stress developed in the case, [MPa]
t_c	Wall thickness of the case, [mm]		

water-jet velocity in the disruptor. Cartridges for this application are explored and developed for the first time, without much inference in the open literature. To achieve the required velocity of water jet by combustion generated gas-pressure, the cartridges are filled with either propellants or pyrotechnics. The choice of the propellant and pyrotechnic is based on the energy requirements and the rate of energy release sought. This pressure-energy of combustion gas produces the required power to operate the system [2].

With the advancement in science and technology, the water disruptor is becoming more popular as a non-contact tool and non-sparking at the target end. The water disruptor is used in the surface preparation industry for cleaning and cutting applications. The water disruptor has a potential to carry out numerous applications in industries such as (i) surface texture, (ii) removal of bulk material in the form of strips or burrs without any heat generation or spark and (iii) compressive stress wave generation for specific applications. These applications have shown high impact in industrial domain. The necessity of water disruptor is dictated by various system parameters like (i) availability of pressure generated by propellant burning inside the cartridge, (ii) water flow through barrel, (iii) stand-off distance, (iv) barrel diameter, (v) jet angle and (vi) exposure time. The pressure generated by propellant burning in the cartridge is dependent on propellant loading density. Different experimental studies were carried out by using the water-jet for making the surface, peening and material removal process. The studies are motivated by practical questions and applications. The objective of this paper is to provide theoretical calculations and technological aspects about the study of bilinear kinematic hardening model of power cartridge and its analysis for water disruptor applications used for destruction of suspected IEDs.

2. Literature Survey

The earliest study stated that brass cartridge case provides the rearward obturation where it is loaded inside the barrel. Syal and Narr [3] carried out the design study of obturator made of brass in combustible cartridge case. The cartridge case was used in tank gun having 105 mm calibre. It was reported that the dynamic firing of combustible cartridge case with cup height 115 mm provides perfect obturation in the tank gun ammunition. Dewangan & Panigrahi [4] had performed the analysis of residual stress used in swage autofrettaged gun barrel. The authors studied the analysis via finite element (FE) method. Their study reported that the geometry should be considered systematically to find out the after effects. Bhetiwal et al. [5] found out that approximately 16% weight reduction is feasible using von-Mises as compared to Tresca criterion for autofrettaged gun barrel. Roy et al. [6] discussed the present and futuristic trends in weapon system. Parate et al. [7] explained design aspects of cartridge, propellant, their testing and performance methodology in closed vessel during development trials. Zhu and Yang [8] reported in their study the derivation of an analytical equation for optimum radius of elastic-plastic material. Gibson, et al. [9] talked about various methods to predict residual stresses in strain hardening, autofrettage thick cylinders which includes Bauschinger effect. O'Rourke patented a disruptor apparatus which was fired from a shotgun [10]. Chiu et al. [11, 12] also obtained a patent for modular disruptor mechanism. Such type of mechanism has an exchange concept of different components which allows it to imitate the firing capabilities of systems. Constantin et al. [13] had studied certain aspects pertaining to water disruptor system due to detonation by high explosives using experimental tests and numerical simulation for water disruptor application. Radomski [14] has performed the analysis related to the effects of recoil and a mathematical model explaining the interior ballistics of a two-chambered.

3. Description and Function of Cartridge

3.1. Description

The cartridge used in water disruptor is made up of brass material. It consists of end plug, case, propellant, separator, pyrotechnic composition, squib and lead wire. The cartridge case has squib at centre with lead wire for making electrical connections. The end plug is made up of brass material. The cartridge case has mating threads for an easy assembly with the end plug which is soldered with foil. The foil is made up of copper. The cartridge is filled with propellant and pyrotechnic composition and separated by a separator (a separator is made up of felt).The double base propellant in the form of powder is used as main filling in the cartridge.

3.2. Function

Squib is crucial part of cartridge as a means of initiation. It has a bridge wire. When electrical energy is supplied to squib it becomes red hot by 'Ohmic' or 'Joule' heating. Squib ignites adjacent pyrotechnic composition which in turn initiates the propellant. The propellant generates hot combustion gas, which leads to the development of high pressure in the confined space, quickly. This high pressure ruptures a copper foil, which creates a plume of water through the barrel of disruptor weapon. Fig. 1 shows a schematic of the power cartridge and its part-details.

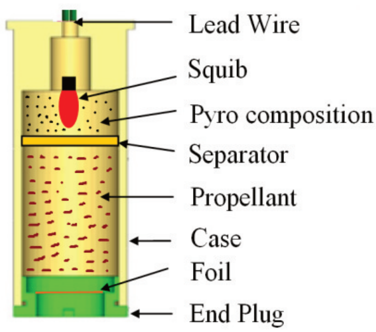

Fig. 1 Scheme of power cartridge showing its detail parts

The cartridge case serves as a container for the propellant, as an obturation device and as a means of assembling the components for easy loading and transportation, etc. The design of brass cartridge case is carried out using the thin cylinder theory where all design specifications are fully satisfied [15]. While manufacturing, cartridge case is lacquered with chromate coating. This acts as barrier between base material and propellant to protect it from the surrounding.

The design of cartridge case must satisfy the following requirements:

- The metallic cartridge case should provide the obturation requirement, i.e. sealing of rearward gases from the gun barrel so that there is no leakage of the gases.
- It must support safety of the propellant during filling, assembly, firing, handling, storage and transportation.
- It should serve as a structural supporting member in the assembly of the cartridge. Further, it allows loading inside the gun chamber.
- It should be easy to extract after the shot or projectile is fired from the gun chamber.

4. Obturation Mechanism

Obturation is one of the important properties of brass cartridge so as to enable easy extraction after the firing. The cartridge has the length and outside diameter of 53 mm and 20 mm respectively. The brass cartridge case is loaded in breech module, keeping a gap of 0.1 mm, generally. This gap is provided between the metal cartridge case and the breech module wall. The cartridge is loaded into the breech module of water disruptor. The engineering drawing of the same is illustrated in Fig. 2. It is provided with 6 annular holes of diameter 3 mm to recoil the water for the weapon. As the cartridge is fired, gases are generated and pass through these annular holes. This gas pressure acts on water inside the compensator. Electroplated chromium coating is applied on it to avoid the corrosion.

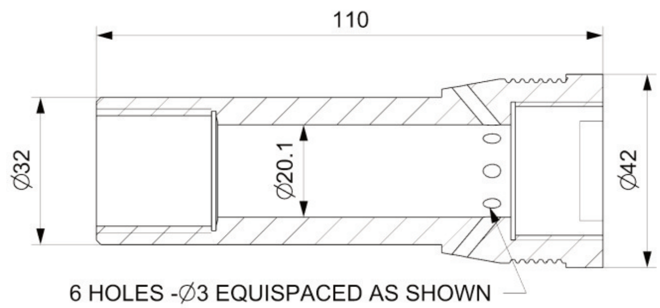

Fig. 2 Engineering drawing of breech module (*all dimensions are in* [mm])

An image of assembly of power cartridge with breech module is illustrated in Fig. 3. Breech module and power cartridge are parts of water disruptor. Breech module was designed in such a way that there is no difficulty in loading the cartridge and extraction of the case after the firing. This activity is manual and mechanical or automated. During the firing of cartridge, the cartridge case expands due to the generation of gas pressure and temperature and it sticks to the walls of breech module. As the expansion of case is within elastic limit, it will return to its original position. The breech module is compatible with ammunition and it is to be designed to withstand firing stresses experienced during the trials. The design of breech module is considered as gun tube based on thick cylinder theory [16]. The cartridge case which is made up of brass material (Cu:Zn = 60:40) has a yield of 395 MPa.

Breech module is made up of steel material and has a yield of 670 MPa. It is hardened to give the required tensile strength. The values of yield stress of these materials were indicated with red colours. The tensile tests were performed using universal testing machine (UTM) on steel and brass materials. The images of test specimen of steel and brass are depicted in Fig. 4 and Fig. 5. The stress-strain graphs of steel and brass were illustrated in Fig. 6 and Fig. 7, respectively.

Fig. 3 Assembly of breech module with the power cartridge

Fig. 4 Steel test specimen

Fig. 5 Brass test specimen

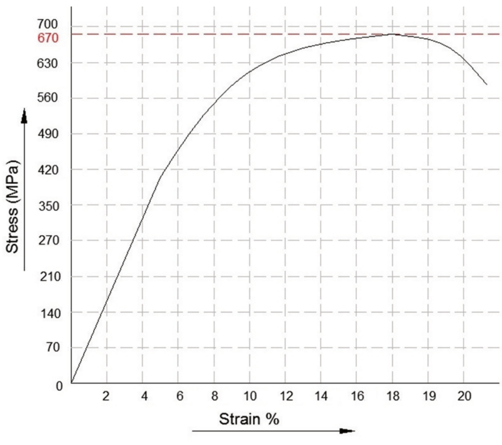

Fig. 6 Stress-strain graph for steel

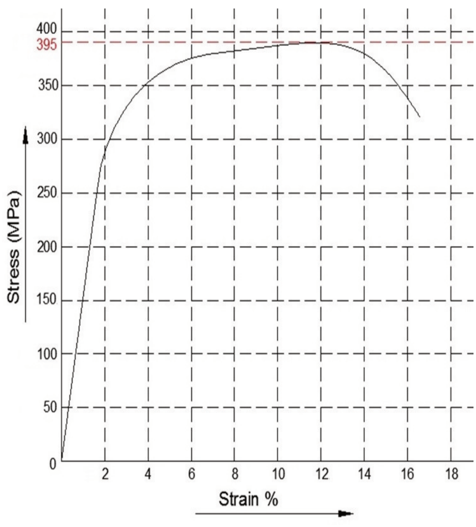

Fig. 7 Stress-strain graph for brass

5. Determination of Stress and Strain

Brass as cartridge case material has been in use since 1600. The design practices were well recognised to realize the requirements as explained above in paragraph 3.2. Still difficulties are noted in the removal of the metallic cartridge case after firing. It can be attached to the breech module or gun barrel wall where cartridge is assembled. This makes the system useless till it is extracted. The case cannot sustain the propellant gas pressure. It is therefore anticipated to support it using a breech module walls. Further, the case is provided with enough clearance to allow proper and easy loading. The designer must look into the sticking phenomena before designing a new cartridge case. This is feasible and using some simple equations, it can be predicted whether the cartridge case will inflate or stick to the walls of breech module of the water disruptor after the firing. The clearance between breech and cartridge case must be sufficient for easy loading. However, the clearance between them should not be as large that excessive plastic deformation or rupture may occur. Graphically, it is shown in Fig. 8. Dotted line in red colour shows low-yield case interference with chamber (breech module) with certain value.

This figure shows low-yield strength of the cartridge case under loads. The contraction and expansion of breech module itself should be taken into consideration. Fig. 9 shows this state and it must be approximated as a bilinear, kinematic hardening model. The stress-strain graphs of a material are modelled. The first step in this exercise is to model the pressure generated by the cartridge. Here, it is assumed that the material behaves in perfect elastic mode. This will be the perfect case for any suitably designed breech module which will also help to determine the radial expansion [17] through Eq. (1).

$$U_{\mathrm{PC}} = \frac{R_{\mathrm{i}}\left[(1-\nu)\left(P_{\mathrm{i}}R_{\mathrm{i}}^{2} - P_{\mathrm{e}}R_{\mathrm{o}}^{2}\right) + R_{\mathrm{o}}(1+\nu)(P_{\mathrm{i}} - P_{\mathrm{e}})\right]}{E_{\mathrm{tube}}\left(R_{\mathrm{o}}^{2} - R_{\mathrm{i}}^{2}\right)}. \tag{1}$$

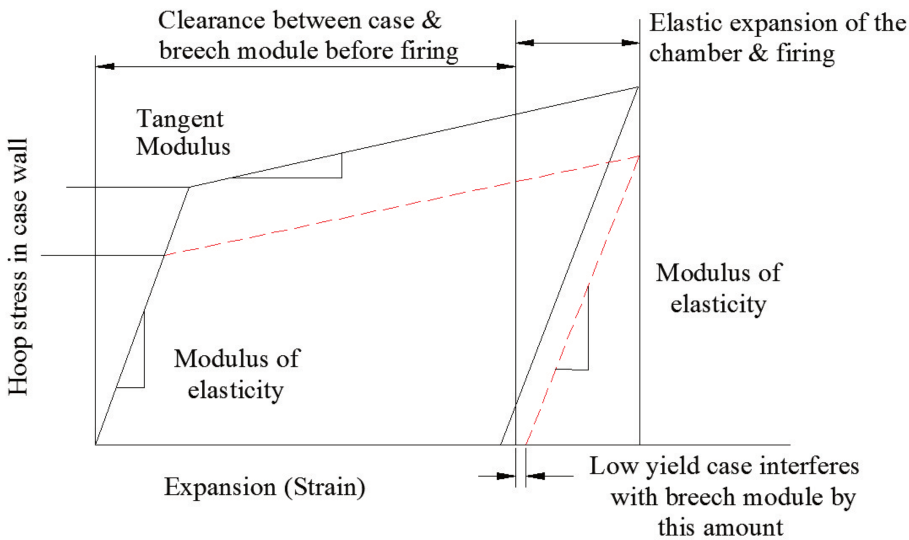

Fig. 8 Stress-strain graph and low-yield strength properties

Eq. (1) was tailored pertaining to thick-walled cylinder. This is the point where the designer is interested in the inner radius of the breech module wall, R_i is the inner radius and R_o is the outer radius of the breech module, P_i is internal pressure, P_e is the external pressure (it is assumed as 0), v is Poisson's ratio for the breech module material, and E_{case} is the modulus of elasticity.

The stress, displacement and strain of the case can be determined with the following equations.

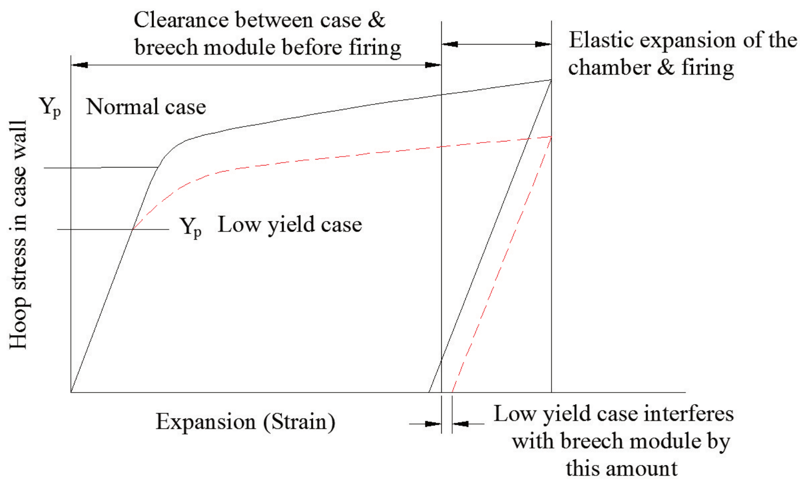

Fig. 9 Stress-strain diagram with low yield strength having bi-linear kinematic hardening materials

$$U_{\text{case}} = \frac{r_{\text{case}}^2 P_{\text{i}}}{E_{\text{case}} t_{\text{c}}}, \tag{2}$$

$$\sigma = \frac{r_{\text{case}} P_{\text{i}}}{t_{\text{c}}}, \tag{3}$$

$$\varepsilon = \frac{\sigma}{E_{\text{case}}}. \tag{4}$$

In the above equations, U_{case} is the radial expansion, σ is the hoop stress, ε is the hoop strain, r_{case} is the outer radius of the case and t_{c} is the thickness of case. As, the expansion of the breech module will stop, the case expands further so that the contact is made to its maximum expansion. This can be expressed as follows:

$$U_{\text{case max}} = U_{\text{PC}} = r_{\text{case}} \varepsilon . \tag{5}$$

Knowing the pressure inside the cartridge case, the breech module dimensions and the value of U_{PC}, maximum strain ε_{max} can be determined. Further, this can be used to estimate the stress at the maximum expansion in the case.

$$\varepsilon_{\text{max}} - \varepsilon_{\text{Y}} = \frac{\sigma_{\text{max}} - \sigma_{\text{Y}}}{E_{\text{case-tangent}}}. \tag{6}$$

In the above equation, the subscript Y shows the yield values and $E_{\text{case-tangent}}$ is the tangent modulus for the cartridge case brass material. The stress was calculated at the maximum expansion. It is observed that a material has shown the yielding and will retract along its original modulus of elasticity. This can be expressed as:

$$\varepsilon_{\text{return}} = \frac{\sigma_{\text{max}}}{E_{\text{case}}}. \tag{7}$$

Therefore, the residual strain in the cartridge is expressed by:

$$\varepsilon_{\text{residual}} = \varepsilon_{\max} - \varepsilon_{\text{return}} . \quad (8)$$

The permanent radial displacement can be found out as:

$$U_{\text{residual}} = r_{\text{case}}\, \varepsilon_{\text{residual}} . \quad (9)$$

The above Eqs (8), (9) were useful to determine the residual strain and permanent radial displacement. Adding U_{residual} to the original radius of the case, r_{case}, it is noted that:

$$U_{\text{residual}} + r_{\text{case}} > R_{\text{i}} \text{ case will stick} \quad (10)$$

or if

$$U_{\text{residual}} - r_{\text{case}} < R_{\text{i}} \text{ case will not stick} \quad (11)$$

The above Eqs (10), (11) were useful to determine if the cartridge case will stick or not to inner radius of breech module.

6. Materials and Methods

Cartridge material is brass, consisting of Cu:Zn = 60:40, with grade I. The dimensions of the cartridge are:

- outside diameter: 20 mm,
- internal diameter: 17 mm,
- thickness: 1.5 mm.

The mechanical properties of brass material are obtained by subjecting it to tensile testingof standard specimen using UTM. The chemical constituents [%] of brass are given in Tab. 1 [18].

Tab. 1 Mechanical properties and chemical composition of brass

Mechanical properties		**Chemical composition [%]**	
Ultimate Tensile strength	395 MPa	Copper	56
Modulus of elasticity	100 GPa	Lead	2
Hardness	90 HV	Iron	0.35
Percentage elongation	12%	Impurities	0.7
Poisson’s ratio	0.33	Zinc	Reminder

The breech module is made up of steel with grade 37C15. The dimensions of breech module are:

- outside diameter: 42 mm,
- internal diameter: 20 mm,
- length: 100 mm,
- internal pressure generated: 63 MPa.

The mechanical properties of breech module are obtained by subjecting it to tensile testing of standard specimen using UTM. The chemical constituents [%] of steel are given in Tab. 2 [19]. The other constituents such as Ni, Cr, Mo, V and Al are not more than 0.8%.

The considerations with above parameters and material properties are illustrated with example calculations given at paragraph 7.

Tab. 2 Mechanical properties and chemical composition of steel

Mechanical properties		**Chemical composition [%]**	
Ultimate Tensile strength	670 MPa	Carbon	0.350
Modulus of elasticity	200 GPa	Manganese	1.350
Hardness	220 HV	Silicon	0.200
Percentage elongation	18%	Sulphur	0.035
Poisson's ratio	0.29	Phosphorous	0.035

7. Results and Discussion

The computation results of an example calculations using the above equations as well as indicated mechanical properties are obtained. The various strain and stress experienced by the cartridge case and the breech module can be estimated by using various formulae explained at section 5. The ultimate and yield stress of 395 MPa and 260 MPa obtained from Fig. 7 are used for calculations. Internal maximum pressure [20] and tangent modulus of elasticity for cartridge case material are taken as 63 MPa and 80 GPa. Hoop stress, longitudinal stress and maximum shear stress for the cartridge are 357 MPa, 178.5 MPa and 89.5 MPa. The longitudinal strain for the cartridge is 0.178×10^{-3}. The radial expansion of case and breech module works out to be 42×10^{-3} mm and 5.25×10^{-3} mm. Hoop strain of the cartridge and radial displacement are estimated as 3.57×10^{-3} and 35.7×10^{-3} mm. Residual strain of cartridge case was calculated theoretically as 1.210. After a detailed calculation, the permanent radial displacement of the cartridge case works out to be 12.1065 mm. It is assumed that the same amount of pressure, i.e. 63 MPa acts on breech module. To determine the various stresses and strains for breech module, thick cylinder theory was used. The calculated stresses, strains and other parameters are given in Tab. 3.

From the Tab. 3 above, it is observed that as ($U_{residual}$+ Outer radius of case) is greater than internal case radius, it will stick to inner walls of the breech module. Therefore, perfect sealing is observed. After the conduct of each firing, smooth extraction from the breech module was noticed in all cases. No hard extraction and bulging of cartridges were noticed. The images of cartridges after series of firings are depicted in Fig. 10. Fig. 11 shows the inside view after the firing.

Fig. 10 Images of cartridges after firings

Fig. 11 Inside view of cartridges after firings

Tab. 3 Calculated stresses and strains of case and breech module

Parameters	**Values**
Hoop stress for cartridge	357 MPa
Longitudinal stress for cartridge	178.5 MPa
Maximum shear stress for cartridge	89.25 MPa
Hoop strain for cartridge (ε)	3.57×10^{-3}
Longitudinal strain for cartridge	0.178×10^{-3}
Radial expansion of cartridge	42×10^{-3} mm
Radial displacement of case	35.7×10^{-3} mm
Strain at yield point (ε_{Y})	0.260×10^{-3}
Maximum strain (ε_{max}) using bilinear kinetic hardening modelling	1.2146
Maximum strain (ε_{return})	0.395×10^{-3}
Residual strain ($\varepsilon_{residual}$)	1.210
Maximum expansion of cartridge case	3.95×10^{-3} mm
Radial clearance	0.1 mm
Permanent radial displacement of cartridge case ($\underline{U}_{residual}$)	22.10 mm
$\underline{U}_{residual} + r_{case}$	11.21 mm
Hoop stress for breech module	56.134 MPa
Radial expansion of breech module	5.25×10^{-3} mm
Hoop strain of breech module	28.067×10^{-5}
Maximum expansion of breech module	840×10^{-5} mm
Longitudinal stress of breech module	40.32 MPa
Radial stress of breech module	24.59 MPa
Shear stress of breech module	15.772 MPa

8. Conclusions

From the foregoing deliberations, it is clear that the design of cartridge case meets the obturation requirements based on the above assumptions. From the above Eq. (10), it is inferred that the case will stick to the walls of breech module and perfect obturation will be obtained. Thus, the escapes of rearward gases are prevented from occurring. Once the gases are released through the barrel, if this expansion is within elastic limit, the cartridge retains its original dimension. This helps in easy extraction of the cartridge after the firing. The same was noticed after the conduct of series of firings. The purpose of providing a radial clearance of 0.1 mm between the cartridge and breech module helps in an easy removal after conducting firing trials in water disruptor. Therefore, the inference is drawn that the brass cartridge case will not stick to the walls of breech module after the firing.

After carrying out the experimental trials of the cartridge case with breech module, the following inferences were drawn:

- the brass cartridge case gives the perfect obturation and permits the easy extraction after static firing trials which meet the requirement,
- in the present paper, an attempt has been made to describe the general design approach of the power cartridge and its bilinear analysis, kinematic hardening modelling for water disruptor application.

9. Conflict of Interests

The authors state that there are no conflicts of interests pertaining to the publication of this research paper.

10. Funding

The author(s) received no financial support for research, authorship or publication of this article. There has been no significant financial support for this research work that could have influence its outcome.

Acknowledgements

Authors are grateful to Dr. K. M. Rajan, *Distinguish Scientist and Director* ARDE, Pashan, Pune – 411 021 for his kind permission to publish this work. The authors also extend their sincere thanks to Shri.V. K. Dixit, Sc. 'H', Associate Director for his invaluable guidance and support. Authors would like to thank Shri V. R. Patil, Sc 'F' and Mrs. Kalpana Tipare, Sc 'D' of Material Testing and Analyis Division for providing tensile testing of steel and brass specimenusing UTS.

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