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Shock Isolation for Shelters

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Abstract: *In recent years, wide studies are carried out in usage of isolators in structures and equipment, for the reduction of vibrations transmitted due to earthquakes, machine vibrations and any other minor disturbances. But providing protection against vibrations caused due to blasts still remains challenging due to its high amplitude and very short duration. In this paper, an effort has been put for providing shock isolation for protective structure against dynamic load caused due to Blast, using mechanical springs devoid of damping. Here an analytical study is made to understand the reduction of 10g acceleration to tolerable limit of 0.5g acceleration. Simulations are carried out using ANSYS software to understand the behavior of the spring under varying static and dynamic loads. Transmissibility of the shock from base to top of the spring is also studied using software and results are found to be comparable with the theoretical approach. The results evident that desired transmissibility can be achieved using mechanical springs*
Keywords: *Ground shock, mechanical springs, shock isolation, transmissibility*

I. Introduction

When a blast explosion occurs, pressure waves with tremendous intensity are transmitted into air and into ground as shock vibration. These waves which propagate radially outward from the vicinity of the explosion will decrease its peak intensity with increase in duration. These waves when imposed on the ground and on structures buried within the earth or on the surface will cause the motions termed as "ground shock". Personnel and equipment housed in structures subjected to these ground shock, require protection against possible injuries or damage which may result from impact forces. Such protection can be achieved by providing energy absorbing system (shock isolation) between the structure and ground which is subjected to vibration.

The purpose of this article is to discuss on the design of mechanical springs as isolators for protection of personnel and equipment against the effects of ground shock caused due to blast explosion.

II. Types Of Ground Vibrations

Ground vibrations generally are of different types depending upon the source which causes the vibration. The common sources of vibration are machines, earthquake, winds, water waves, traffic, construction works and explosions. The nature of vibrations caused by these sources is classified [7] as shown in the Fig. 1,

Figure 1: Types and Sources of vibrations

In case of earthquake, maximum amplitude generally occurs after sometime from the onset of the earthquake and persists for certain duration of time. In contrast, Shock wave due to blast causes vibrations which has very high amplitudes with very short time durations. The peak occurs immediately after the onset of the shock on the structure. The vibration patterns produced by machines, earthquake and blast are as shown in the following Fig. 2,

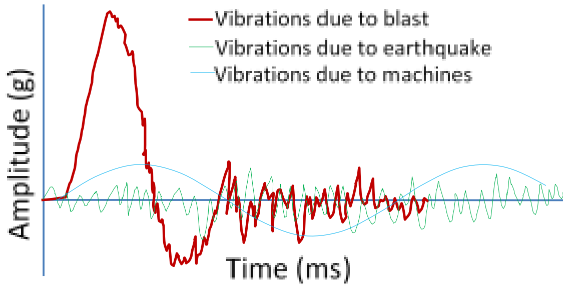

Figure 2: Vibration pattern

III. Effect Of Dampers On Vibrations

In case of Harmonic vibrations, dampers are very effective and useful in controlling the amplitude of vibration as it doesn't die out. Thus here a combination of spring and dampers shall be effective as isolator. Dampers have reasonable contribution in case of vibrations caused due to earthquake, as the vibrations are not constant and continuous over a longer period of time. The concept of damping does not have much significance in case of Impulse loading [8]. This is because, the load with maximum amplitude acts for very short time duration within which the dampers cannot absorb the energy, but it may help to reduce the vibrations caused due to the impact of maximum wave. This study is undertaken ignoring the effect of external dampers and inherent damping in the isolation.

IV. Ground Shock Phenomena

Air burst, surface burst and underground burst are the three major phenomena that causes vibrations on the ground [2]. These phenomena are described for basic insight with pictorial representations,

4.1 Air burst

In Air burst, explosions occurs above ground and the pressure waves directly hits the ground before it hits the structure. This causes shock vibrations in the ground. Fig. 3 gives the representation of air burst.

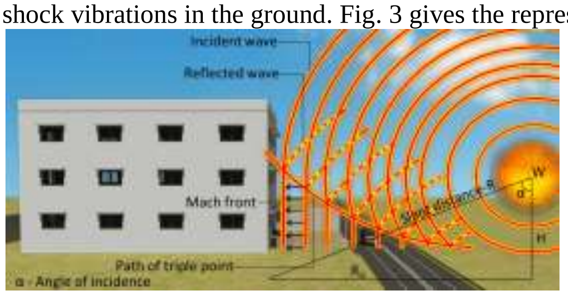

Figure 3: Air burst

4.2 Surface burst

This type of burst transfers the shock directly to the ground as it occurs on the surface of the ground. This type of blast forms crater at the point of detonation. The intensity of shock vibration transferred in this type will be higher when compared with the air burst. Fig. 4 represents surface burst.

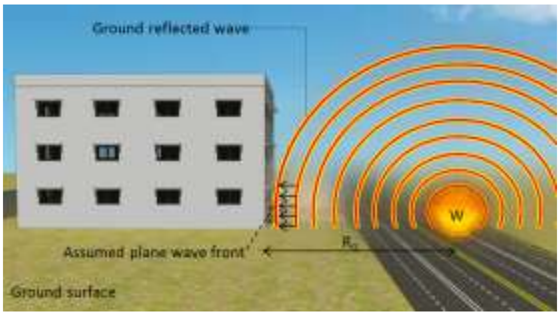

Figure 4: Surface burst

4.3 Underground burst

This type of burst occurs in the underground and has very high impact in creating vibration in the ground. This will cause crater at that location. The vibration transferred to the ground in this type of blast will be very high. Fig. 5 denotes Underground burst.

Figure 5: Underground burst

V. Effects Of Ground Shocks

The vibrations has various ill effects on the structure, equipment [2] and personnel [1] as discussed below,

5.1 On Structures

Vibrations when acting on the structures causes oscillations in vertical and horizontal directions. This causes larger magnitude of shear force at the base of the structure and other secondary effects which may be very much destructive. The concept of Resonance is unlikely as the natural frequency of the structure and the blast will never match.

5.2 On Personnel

The effect of vibrations on persons depends upon magnitude, duration, frequency, rise time, body positions and restrains. While experiencing the vibration, human body undergoes longitudinal effect where the acceleration acts on the entire body parallel to the spine, transverse effect where the acceleration acts normal to the spine and whiplash effect where the head moves with respect to shoulders either forward and backward or sidewise. An indicative representation of bodily motions under horizontal acceleration is represented in Fig. 6.

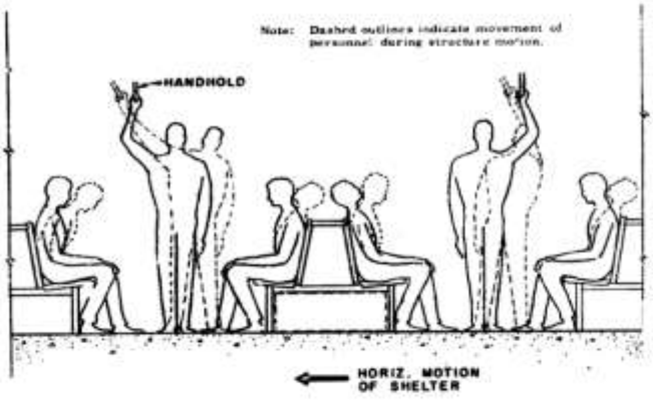

Figure 6: Effect of vibrations on personnel

5.3 On Equipment

Equipment may undergo temporary or permanent failures due to the effect of external vibrations acting on them. Temporary failures shall include malfunctions of the equipment for either short or long time depending upon the extent of damage. Permanent failure includes breakage of the equipment and its dis-ability to serve. Equipment which has to be in operating mode during emergency needs mandatory shock isolation for its un-interrupted operation.

VI. Intensity Of Vibration

The intensity of vibrations caused due to blast explosion is very much greater than the accelerations felt due to earthquakes. To highlight the multi-fold severity of blast vibration, a comparison of vibration intensity of earthquake and blast vibration intensity is presented in figure 7. The earthquake parameters adopted are, Zones-II to V, Importance factor of 1.5, Sa/g factor of 2.5 and response reduction factor of 2.5. Blast vibration parameters are 1000 pounder TNT at a distance of10m and 15m from the structure. It can be observed that earthquake induced vibration is 0.27g and blast induced vibration is 9.61g, which is around 35 times higher than the earthquake induced.

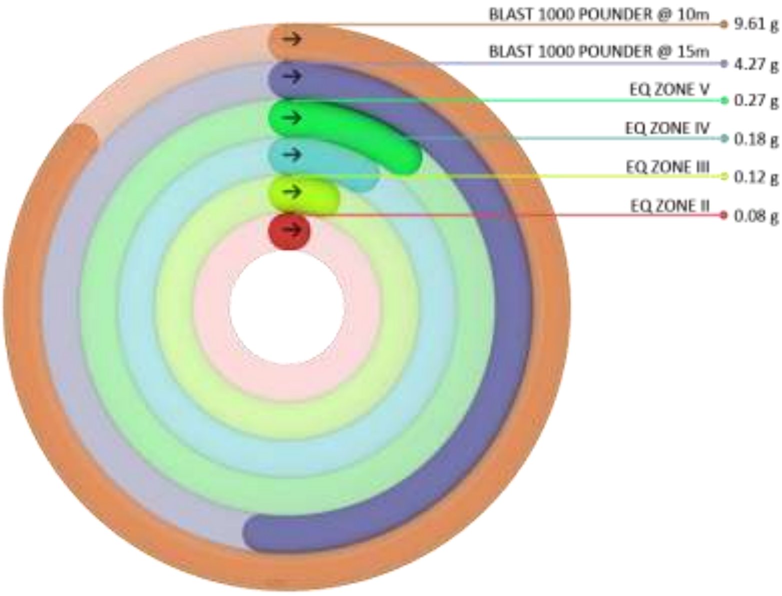

Figure 7: Intensity of vibration

It is evident that the vibrations caused due to blast explosions are manifold times the vibrations caused by earthquake and this makes the isolation more challenging and complicated.

VII. Concept Of Shock Isolation

Shock is a condition where a single impulse of energy produced by a force is transferred to a system in a short period of time and with large amplitude. The purpose of shock isolation is to limit the forces transmitted to tolerable levels of the system to be protected. The systems that can be protected are structures, personnel and equipment. The tolerance level in case of protecting the structure will be the maximum tolerable limit for personnel and for equipment, the tolerable limit of most sensitive equipment will be considered. The Isolators reduces the shock by undergoing deflection and releasing the energy over a longer period of time. The tolerance level for human beings, at various postures, as-listed in TM-858-4 is tabulated in Table 1,

Table 1: Tolerance limits for human

	Posture	Criteia	Shock Direction		
			↑	↓	⟷
	Unrestrained standing	A B	10g 0.75g	- 0.5g	* 0.5g
	Unrestrained sitting	A B	15g 0.75g	- 1g	* 1g
	Unrestrained prone	A B	40g 0.75g	* 1g	* 0.75g
	Restrained sitting	A	15g	15g	15g
	Restrained Prone	A	40g	40g	15g

* Displacement must be limited, i.e attenuated to less than the distance between operator and nearest solid object

A = Limited g value to prevent internal Injury

B = Limited g to prevent possible impact injury

The mentioned tolerance levels shall be ensured through the concept of Transmissibility.

In this study, mechanical springs are used as isolators to control and reduce the vibrations to tolerable limits.

7.1 Mechanical Springs

These types of isolators can be used for isolation purpose as it has the capability of restoring back to its original position once the applied load is removed. Both axial and lateral loads can be resisted by these types of springs, but comparatively lateral capacity of these kind of spring is much lesser than that of vertical capacity. Mechanical springs are adopted for this study, as it also has higher temperature resistance as compared to elastomeric isolators.

7.2 Effect of Spring Material

7.2.1 Carbon steel

Carbon steel springs are most commonly used when compared to other types as they are less expensive and readily available. These types of springs shall be used in the case of structures with less weight and for low intensity blast loads.

7.2.2 Chromium steel

The alloy steel springs are generally used under conditions involving high stress and for shock applications where impact loading occurs. Alloy steels can withstand higher and lower temperatures than the high-carbon steels and are available in either the annealed or pre tempered conditions.

VIII. System Of Isolation

An Isolation system shall be coupled system or uncoupled system [2]. In case of coupled system, transition or rotation along one orthogonal axis causes response along other axes. In case of uncoupled system, transition or rotation along one axis causes response in the same axis. If the principal elastic axis and inertial axis coincides at the center of gravity of the mass, then such system is called a balanced system which is most preferred. The Fig. 8 explains the concept of coupled and uncoupled system. At point A, elastic center (EC) of spring system and the center of gravity (CG) of mass coincides forming an uncoupled or balanced system. If the CG of the building lies at point B, then the motions parallel to X axis alone is uncoupled. If the EC of spring system and CG of the building lies at point C, then the motions in any directions are coupled.

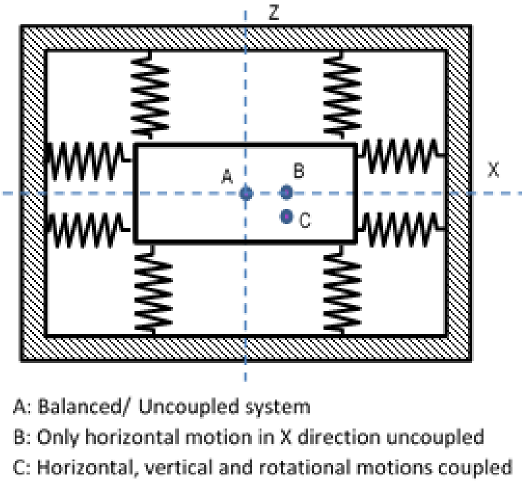

Figure 8: System of Isolation

The basic spring parameters required for the design of spring isolators are described as follows,

IX. Spring Design Parameters

9.1 Shock Transmissibility, Ts

Transmissibility is the ratio between the vibrations experienced by the structure to the disturbing vibration. With this concept, the acceptable tolerance limits shall be obtained. It is represented using (1),

$$\mathbf{T_s = g_o/g_d} \qquad (1)$$

Where, T_s = Shock transmissibility
g_o = Allowable limit of vibration
g_d = Disturbing vibration

Here in this study, the allowable limit of vibration is 0.5g and the disturbing vibration is 10g. Thus the transmissibility will be 0.05 in this case.

9.2 Shock Natural Frequency, f_n

The Natural frequency of shock is calculated from transmissibility relations established based on the shape of the shock pulse. The transmissibility equations for various pulse shape is given below [3],

Pulse shape	**Transmissibility Equation**
Blast or Ramp	$T_s \equiv 3.2\ f_n\ t_o$
Square wave	$T_s \equiv 6\ f_n\ t_o$
Half sine wave	$T_s \equiv 4\ f_n\ t_o$
Triangular wave	$T_s \equiv 3.1\ f_n\ t_o$

Here, the relation corresponding to blast pulse is taken for the calculation of shock natural frequency, i.e

$$T_s \equiv 3.2\ f_n\ t_o \qquad \text{- - - - - - - - - - - - - - - (2)}$$

Where, T_s = Shock transmissibility

f_n = shock natural frequency

t_0 = shock pulse length (seconds)

Indian Standards does not provide sufficient guideline for the calculation of duration of ground shock. Also, limited literatures are available for the calculation of the same. UFC codes provide guidelines for the calculation of shock pulse length in case of Air shock but not for Ground shock. In reality, the duration of shock pulse in air will be more when compared to the duration in ground. Ground shock has lesser duration due to the particle density of ground. Here, the shock pulse length is calculated considering Air shock, i.e. a value which will be more than the actual pulse duration in ground, thus Shock natural frequency is calculated using (3), which is obtained by rewriting (2),

$$f_n = T_s/(3.2 * t_0) \qquad \text{- - - - - - - - - - - - - (3)}$$

9.3 Dynamic Deflection

In addition to the static deflection, spring also has to undergo dynamic deflection when the structure is subjected to 10g acceleration. The dynamic deflection that the spring has to undergo for the protection of the structure from the shock is derived using (4),

$$\Delta_{dyn} = \frac{g_0}{0.102 f_n^2} \qquad \text{- - - - - - - - - - -(4)}$$

9.4 Dynamic Spring Rate

The dynamic spring rate required for the spring to undergo the dynamic deflection is calculated using force to deflection relation given by (5),

$$K_d = W / \Delta_{dyn} \qquad \text{- - - - - - - - - - - - - (5)}$$

The above equation is re-written as follows by substituting (4)

$$K_d = \frac{fn2\ W}{9.8} \qquad \text{- - - - - - - - - - - - (6)}$$

Where, K_d = Dynamic stiffness of the spring

W = Weight of the structure

f_n = Shock natural frequency

9.5 Static Spring Rate

The static stiffness required by the spring to withstand the static deflection is calculated using the following empirical relation,

$$k_s = k_d / 1.4 \qquad \text{- - - - - - - - - - - - - - - -(7)}$$

9.6 Static Deflection

The deflection of the spring under static condition is derived from the total weight of the structure and the static stiffness calculated using the above empirical relation as follows,

$$\Delta_{sta} = W / k_s \qquad \text{- - - - - - - - - - - - - - -}$$

(8)

Where, W = Weight of the structure

K_s = Static stiffness of the spring

Having calculated the spring parameters like Static stiffness, Dynamic stiffness, Static deflection and Dynamic deflection, the design of the spring incorporating the same has to be done. Study of behavior of the spring under static and dynamic loads contributes to precise arrangement of the system.

X. Behavior Of Spring Under Static And Dynamic Load

The core design of the shock isolation system relay upon the layout of springs. This requires a detailed study on the behavior of springs under static and dynamic loads. In the design life of structure, it may be exposed to higher super imposed dead loads and live loads which plays a vital role in the behavior of springs for isolation.

An analysis on a single spring is done using ANSYS to study the behavior of stiffness, transmissibility and deflection under static and dynamic loading. A spring model of 500mm diameter and 50mm wire diameter is modeled and placed between steel plates of size 0.7m x 0.7m. This study is done by varying vertical and horizontal load both dynamically and statically.

BEAM188 element, which connects two nodes and has six degrees of freedom at each node is used for modeling the coil and SHELL181 element, which is a four nodded element, with six degrees of freedom at each node, is used for modeling the top and bottom plates. Bonded contact is used to make both elements to act as single unit. The load acting on the spring is applied as lumped mass over the plate. In static analysis, base of spring is considered as fixed to estimate static deformation. In case of transient analysis, velocity-time relation corresponding to 10g acceleration is applied as boundary condition at base.

10.1 Static Studies

10.1.1 Varying Vertical load

In this case, the spring is acted upon by varying vertical load and exposed to a constant horizontal load of 1000N. The Fig. 9 represents the vertical and horizontal stiffness behavior of spring under varying vertical load. It shows that the vertical stiffness increases with the increase in vertical load. This load acts as a constraint for the deflection in horizontal direction of the spring under horizontal load, thus decreasing the horizontal stiffness.

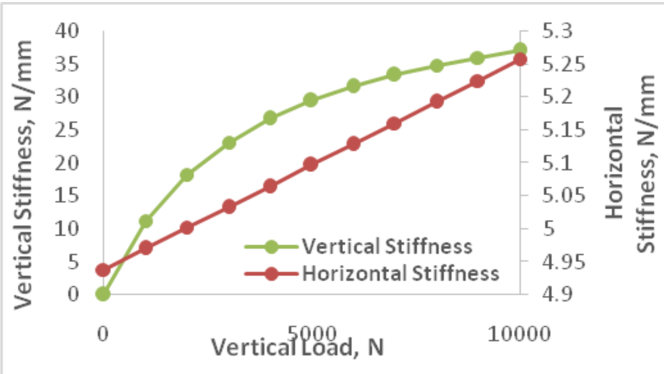

Figure 9: Stiffness Variation-Horizontal Load Constant

10.1.2 Varying Horizontal Load

The Fig. 10 represents the variation of vertical and horizontal stiffness under constant vertical load of 1000N and varying horizontal load. It is observed that both horizontal and vertical stiffness decreases with increase in lateral load. Vertical stiffness is found to decrease as the spring becomes weaker in vertical direction due to P - Δ effects. Reduction in horizontal stiffness can also be attributed to the same reason, but the reduction is not so significant.

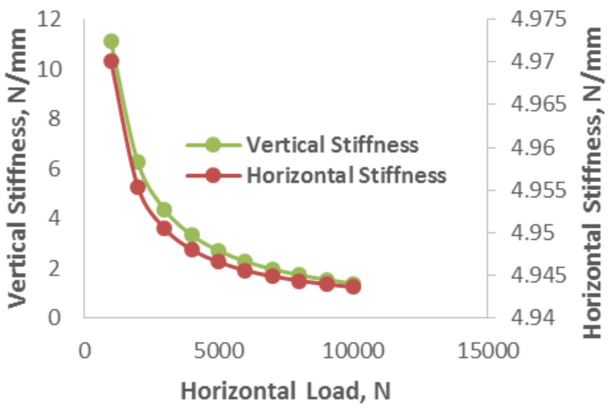

Figure10: Stiffness Variation-Vertical Load Constant

10.2 Dynamic Studies

This study gives us an insight about the transmission of the ground vibration into the above supported structure through the springs. This can be done only through dynamic analysis as this is time dependent. In this case, the analysis is done for a varying vertical load of 900kg and 1000kg on the spring, subjected to acceleration in vertical direction with varying duration. Ansys analysis showing the reduction in acceleration experienced at the spring top against the acceleration applied at the spring bottom is represented in the Fig.11. The Fig. 12 shows the behavior of transmissibility under two loads, 900kg and 1000kg for different duration of impulse.

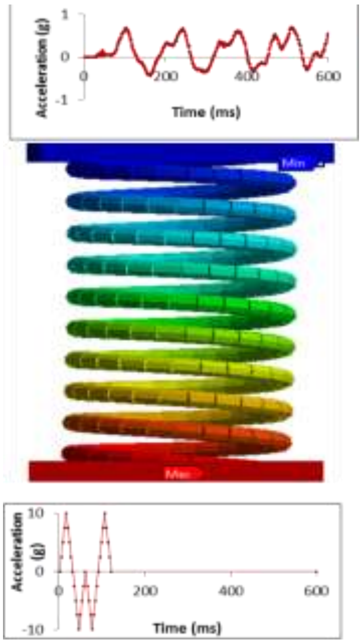

Figure 11: Analysis result for spring subjected to 10g acceleration

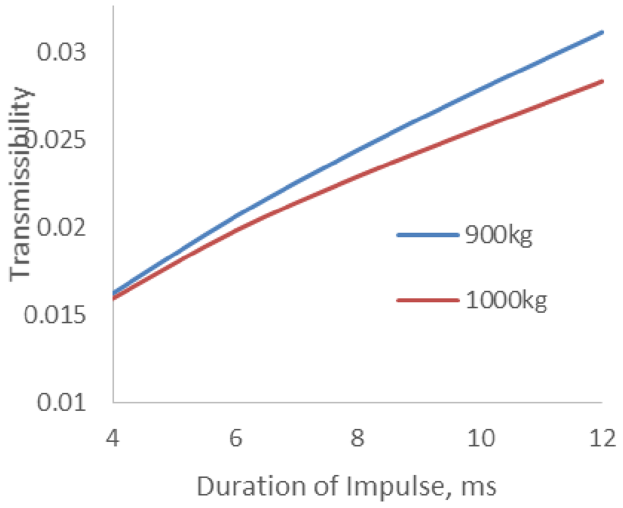

Figure 12: Transmissibility achieved for 900kg and1000kg loading

10.3 Inference

10.3.1 From static Studies

1. Under varying vertical load and constant horizontal load, it is inferred that the vertical stiffness increases with the increase in the vertical load and constant horizontal load. The increased vertical stiffness acts as a constraint for the horizontal deflection under horizontal load.
2. Under varying horizontal load and constant vertical load, the horizontal stiffness of the spring decreases with increase in horizontal load. This is due to the P-Δ effect and decreased stability of the spring.

10.3.2 From dynamic studies

1. The behavior of the spring under dynamic load is entirely different. As the load on the spring is increased for an amplitude of vertical acceleration and certain duration, the vibration transmitted is found to decrease. This reduction in transmissibility is due to the mass on the isolator which resists the acceleration acting for short duration. The vibration transmitted (transmissibility) is found to increase only with the increase in the duration of acceleration acting. As the duration of force (acceleration) pushing the mass above increases, the transmissibility increases. Thus, the successful usage of the mechanical spring, depends upon the study of its complex behavior under static loads, dynamic loads, and direction of the dynamic load.

XI. Spring Design

The Isolator can be designed as helical coil with the spring parameters mentioned

11.1. Spring stiffness

The axial spring rate of helical coil spring is given by following relation,

$$K = \frac{d^4 G}{8D^3 N} \qquad \text{--------------(9)}$$

Where, d = Spring bar diameter

D = Nominal spring diameter
G = Shear modulus for spring material
N = Number of active coils

From the above equation it is clear that combinations of coil diameter, spring diameter and number of active coils will satisfy the required spring rate. Active coils are those coils which are responsible for spring's reaction to loads or displacements and Inactive coils are those that helps to provide attachment.

11.2. Total deflection

Spring undergoes bottoming out condition when it is fully compressed without any space in between them. In such a condition a factor of safety against bottoming has to be considered with the total deflection calculated. Total deflection is calculated using (10),

$$\Delta_t = C_f (\Delta_{st} + \Delta_{dyn}) \qquad \text{- - - - - - - - - - - - - - - - (10)}$$

Where, Δ_t = Total deflection
C_f = Factor of safety against bottoming
Δ_{st} = Static deflection of spring
Δ_{dyn} = Dynamic deflection of spring

11.3. Shear stress check

The main property of the spring is that it has to regain back to its original position once the externally applied load is removed, that is it shouldn't undergo inelastic deformation. In order to prevent inelastic deformation of the spring, the coils of the spring are designed such that the elastic shear strength is not exceeded under full compression. The maximum compressive load is given as below,

$$P^* = k\,\Delta_t \qquad \text{- - - - - - - - - - - - - - - - -- (11)}$$

Where, k = Stiffness of spring
Δt = Total deflection of spring

The maximum shear stress under the compressive load is defined by following (12),

$$\tau_{max} = K\,\frac{8p*D}{\pi d3} \qquad \text{- - - - - - - - - - - - - - -(12)}$$

Where, K = Wahl's correction factor which accounts for direct shear and curvature effect of spring given as $\frac{4C-1}{4C-4} + \frac{0.615}{C}$

C = Spring Index
P* = Maximum compressive force
D = Spring diameter
d = Coil diameter

The maximum shear stress calculated should be lower than the shear strength of the spring material.

11.4. Lateral Stiffness

Every helical spring possess certain amount of lateral stiffness. Assessing the lateral stiffness of the spring provides an insight about the requirement of spring in lateral direction. For compression springs under vertical and lateral loads with Young's modulus E=30000000PSI (2.07 X 1011 N/m2) and G = 11500000PSI (7.93 X 1010 N/m2), Harris –Crede has given the following relation for lateral spring rate

$$K_h = \frac{F_h}{\Delta_h} = \frac{6.89\,10^7\,d^4}{ChN(0.204Hs^2 + 0.265D^2)} \qquad \text{- - - - - - - - (13)}$$

Where, k_h = Lateral stiffness
F_h = Lateral Force
Δ_h = Lateral deflection due to horizontal force
C_h = Factor depending on Δ_{st} / H and H/D
H_s = Compressed height of spring (h - Δ_{st})

The factor C_h can be obtained from figure 8-10 of TM 5-858-4

** (The above equation is applicable only for the specified Young's modulus and Bulk modulus)

11.5. Spring Surge check

When there are impact loads on the springs, the stress propagates along the spring wire. The end coil of the spring in contact with the applied load takes up whole of the deflection and then it transmits a large part of its deflection to the adjacent coils. This wave of compression travels along the spring indefinitely. Resonance might occur depending upon time traveled. This results in very large deflections and correspondingly very high stresses. Under these conditions, it is possible that the spring may fail. This phenomenon is called surge. It is important that the springs used for isolation be checked for the occurrence of Surge. It can be avoided by keeping the natural frequency of the spring 15 – 20 times away from frequency of the shock acting on it. The natural frequency of spring can be calculated using the below relation,

$$f_n = \frac{d}{2\pi D^2 n}\sqrt{\frac{6Gg}{\rho}} \qquad \text{- - - - - - - - - - -(16)}$$

Where, d = Coil diameter
D = Spring diameter
n = Number of active coils
G = Rigidity Modulus
g = Disturbing vibration
ρ = Density of material used

11.6. Rattle Space Requirements

It becomes necessary to calculate the rattle space requirements in order to plan space for the spring arrangement. This value shall be obtained from maximum vertical and horizontal displacement.

XII. Conclusions

The following points are discussed and inferred from the study made

- Mechanical springs are preferred to be a suitable option for the isolation of protective structure from shocks due to blasts.
- Analytical study on the behavior of the springs is made under static and dynamic loads.
- From static analysis, the increase of vertical load under constant horizontal load, increases the vertical stiffness of the spring making the system rigid. The increase in load in horizontal direction under constant vertical load, decreases the horizontal stiffness of the spring and makes the system instable.
- In case of dynamic loading with vertical acceleration, the increase in vertical load reduces the vibration transmitted to the structure from the ground, as the increased load acts like a constraint for movement of the spring. The increase in the duration of the impulse, increases the vibration transmitted into the structure.
- Though the behavior of the spring under horizontal acceleration is not covered in this paper, it is suggested to provide horizontal springs as they help in reducing the transmissibility in horizontal direction.
- Efficient isolation system using Mechanical springs can be achieved by fully understanding the behavior in all the three orthogonal axes under static and dynamic loads.

XIII. Scope For Future Work

Combined action of vertical and horizontal springs further reduces the transmissibility into the structure. This combined effect shall be studied both analytical and numerically. Contribution of the effect of external and internal damping in reducing the after effects of the impulse load on the structure can be studied.
Strain hardening might reduce the efficiency of the spring due to plastic deformation. A detailed study incorporating the effect of strain hardening shall be done to verify the effectiveness of the spring.

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