Response of Structural Members to Dynamic Loading and Suggestions of Protection Systems

Adnan I. O. Zaid

Abstract— In quasi-static loading where the inAvolved strain rates range from10^-4/s to 1/s and the time involved varies from seconds to months and even years. In this type of loading some of the engineering structural members might attain their full design loads during their life time. However, in intermediate rate and high strain rate loading where the strain rates vary from 1 to 10^2/s in the first and from 10^2 to 10^4/s in the latter, the time involved in these systems is of the order of milliseconds and microseconds respectively, and much less than this in the case of nuclear bombardments. As a result of these short times, failure and fracture may occur in certain parts of the member whereas other parts are not reached by the impulse load. In this paper, different designed systems to protect the structural members are presented and discussed. The suggested design systems include the previous methods and new suggested alternative methods which include superplastic materials and equal channel angular pressing, ECAP, as heavy plastic deformation process for absorbing the force and energy of the dynamic loads. The paper is expected to be of importance and value to design engineers civil, architectural and mechanical engineers.

Index Terms— Dynamic Response, Fracture, Protection Systems, Stress Waves, Structural Members.

1 INTRODUCTION

Structural engineers, in most cases, do not consider the dynamic behavior of the materials in the design of buildings, bridges and structural members. This is the reason, most of the early published theoretical and experimental research work on the response of different structural members was investigated under quasi-static loading condition; despite the fact that the behavior and response of materials and members is quite different. In quasi-static loading, the stresses are transferred through the loaded material by the particles of the material whereas stresses in the dynamic loading are transferred by waves referred to as stress waves which differs according to the type of dynamic load e.g. longitudinal waves in case of tensile and compressive waves where they travel with speed equals (E/p)^1/2, where E is the modulus of elasticity and p is the material density and it has the same value of the acoustic speed of the material, and shear waves incase o torsional or shear loads, where they travel by a speed equals (G/p)^1/2, where G is the modulus of rigidity of the material.

This is obviously inadequate particularly in regions liable to earth quakes and seismic conditions. In such situations, some accounts of the dynamic properties of the constructional materials should be taken into consideration for safe designs of buildings and bridges. The first reported research work on the subject seems to be during the Second World War when some researchers have investigated the effects of bomb blast on buildings, ships and on submarines, [1,2,3]. Ever since, researchers started to consider the dynamic response of different structural members, [4,5,6,7, and 8]. Over the subsequent years more appreciation of the effects of stress waves caused by the impulsive or dynamic loading and blasts on the mechanical properties of materials at high rates of strain were considered and conferences were held worldwide on the subject, [9,10 and 11]. Since then, engineers had begun to unshed their unquestioning belief in the sanctity of linear elastic methods of analysis and design had been awakened to the relevance of concepts based on dynamic response. Different geometrical shapes of structural members were investigated. These include: beams, columns, plates and shells. The literature on these members is reviewed and discussed in detail in ref.[12]. This is supported by the experimental observations when a conical rod is subjected to dynamic load, fracture might occur in certain part of the rod before another part of the rod is not reached by the stress wave.

1.1 protection Systems

The automobile, aircraft and space vehicles industries are striving to protect their products against crashworthiness and damages caused by meteoroids and terrorist acts. This is achieved by designing new shielding systems and selecting appropriate materials, e.g. metal matrix composites, powder compacted and superplastic materials to be used in the manufacturing of the new designs. These newly developed materials are now widely used due to their superior properties e.g. high strength – to- weight ratio, high ductility, etc. A need for implementing them into practical use has arisen. Because of their favorable and unique features, they have great potential in manufacturing many industrial and engineering parts. However, an adherent gap exists between the research and the industrial field to push these materials into usages. For newly produced materials to be shaped and formed into their final shape and become traditionally used further research is required. In this section the previously used methods for protection of structural members from damages caused by dynamic loads are reviewed and new suggested methods are also given and discussed.

• *Adnan I. O. Zaid is currently a full professor in Mechanical and Industrial Engineering Department, Applied Science Private University, Amman 11931 Jordan. E-mail: adnan_kilani@yahoo.com*

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2 PREVIOUS USED METHODS

2.1 Double and Multi-Layer Shields

In this type the shields are composed of an external bumper shield that is first exposed to the impulsive load or projectile impact which causes the projectile to completely fracture or disintegrate during impact. The resulting fragments of the projectile and the shield materials that form behind the bumper leads to a much wider spatial and temporal distribution of momentum, hence allowing weakening of the stress level in the pulse, allowing the back wall of the shield to withstand the remaining impact pressure. It has been demonstrated that fractures and damages can, in many cases, be reduced by employing the double or laminated shields, [12,13]. The results of the experimental work have served to alert the design engineers to the possibility of damage by the use of laminates. It is also realized that it is not possible to test all the possible laminates, [14]. It is worth mentioning that the design engineer should realize that the use of laminates does not necessarily reduce the possibility of fracture or damage, but may in some cases result in an increase in damage to the structure, [15,16 and 17]. The first paper on the use of multi-plate targets in high speed impact appears to have been published in 1916, [18]. The results of this work – in the ballistic range- indicated that a single plate target is preferable to a laminated one of equivalent total thickness, and it was stated that the depth of penetration of the projectile in the former case is 89.8% of that of the latter case.

Experiments on 0.2% C steel plates by rifle bullets were carried out in 1930 obtained similar results to those of ref. [19], and gave the above respective penetration as 79% [20]. The explanation offered in both references was, essentially, that a multi-plate has a lesser resistance to penetration due to the absence of cohesion between the plates. In the same year Hagiwara carried out similar experiments on aluminum plates and reported that no difference existed in the resistance to penetration of multi-plate and single plate targets. While there appears to have been little further work carried out in the inter coming years, interest in the use of multi- plate shields was stimulated and proposed that penetration damage inflicted on the wall of a spacecraft could be greatly reduced by placing a thin shield –a bumper – a short distance away from the wall. It was also reported that meteoroids would be extensively fragmented or vaporized during the penetration of the thin shield so that their ability to penetrate the main wall thereafter is drastically reduced, [21]. A further advantage in the use of multi-plate shields, according to what was reported in ref. [22] is the reduced tendency for the shield to spall and hence an improvement in the resistance to perforation is achieved. From the examination of the available literature it seems that there are several parameters distinctly affecting the performance of multi-plate shields, and these are now considered below.

i). Spacing of the plates: in general, the effectiveness of a bumper increases as the spacing increases, but only to an optimum spacing, after which there is no further increase. This was demonstrated in ref, [23], in examining the penetration of o.o62 inch diameter copper spheres into aluminum target at an impact velocity of 8ooo ft/s. It was also observed that whilst spacing has a significant effect at 8000 ft/s, it has little effect at 12000ft/s. The present authors are of the opinion however, that this apparent inconsistency may be due to the closer approach to cratering conditions, with increasing impact velocity [24]. Simple description of cratering is, an impact situation where the front end of the projectile is displaced laterally continuously during impact, under the high stresses generated, until it is entirely consumed, [25].

2.2 Use of Stiffeners

At the beginning of the tests, it was thought that the stiffener should be welded to the target plate or fixed to it with araldite to keep it in the pre-determined position during the perforation process. preliminary tests with the stiffeners placed on the target, with and without fixation, showed that the stiffener was rigid enough to stay in its position in both cases. it was then decided to place the stiffener on the top of the plate without fixation and it was found that in all the tests covered by present investigation the stiffener remained in position. Examination of the plate after penetration indicated that the shearing starts in the stiffened part of the plate, indicating that the stiffened part of the plate is weaker than the rest.

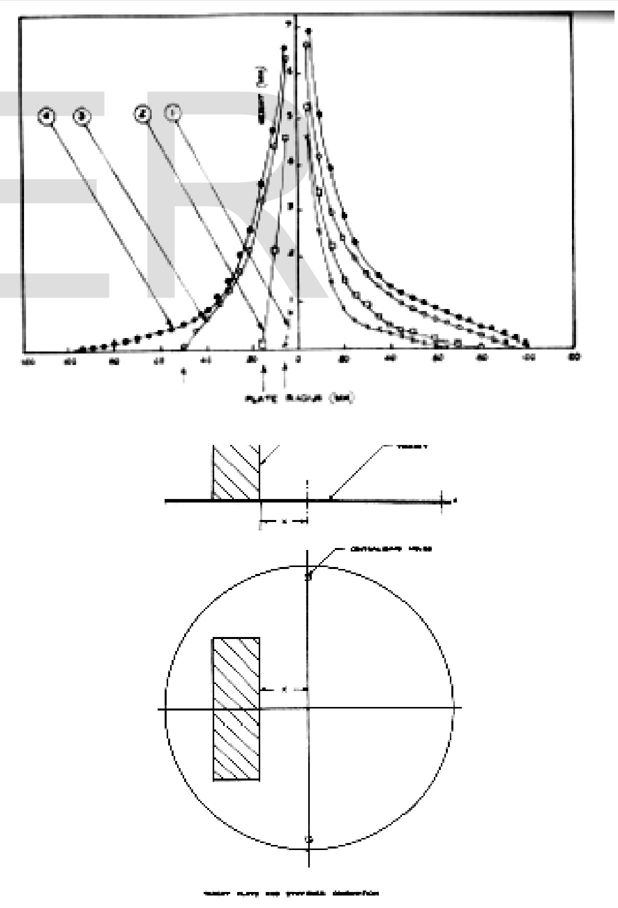
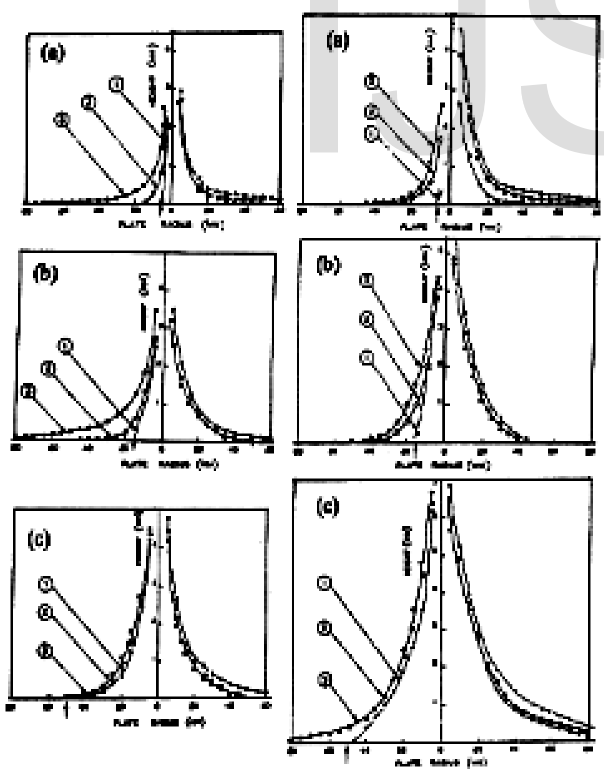


Fig. 1. Profile of the plates with the stiffener at different positions from the center

3 MODE OF DEFORMATION

Examination of the perforated plates indicated that introducing the stiffener to the plate reduces the amount of bulging encountered in it, especially in the region near to the stiffener. Furthermore, they indicated that the amount of bulging and the maximum affected diameter in the target, are smaller in the plane perpendicular to the axis of the stiffener than those measured in the plane parallel to the axis of the stiffener. It was also found that the amount of bulging was affected by the distance of the stiffener from the center of impact: by increasing the distance of the stiffener from the center of impact the amount of bulging increased and when the stiffener was placed at 50 mm from the center of impact, the amount of bulging became comparable to that when no stiffener was used. This can be explained as follows: form the experimental observations of it was found that the amount of bulging is maximum at the center of impact and drops rapidly away from the center, and since the stiffener acts as an arrester to the plastic deformation therefore, the nearer it is to the reign where the plastic deformation is great, the more adverse effect it will have. This is very clear from the areas under the profiles of Fig.2. It was also found that the shape of the holes in the target and the recovered plugs were unlike those of the non-stiffed conditions; the hole was found to be oval in the stiffened condition whereas it was almost circular in the non-stiffened condition.



(A) (B)

Fig. 2. (A) Profiles of o.85 mm thick plate, at containment and (B) profiles of 1.5mm thick plate at containment

Note: (a), (b), and (c) are the profiles with the edge of the stiffener at 5, 15 and 50 mm from the plate center respectively. Profiles 1, 2 and 3 refer to the directions perpendicular, inclined 45° to the stiffener axis for both Figs. 2 (A) and (B).

4 EFFECT OF PLATE THICKNESS

Examination of Fig.3 and the results in table 1 illustrate that, by increasing the plate thickness, (whilst keeping the stiffener in the same position) the ratio of Est/Eo (the energy required for contaminant of the stiffened plate to that required for containment of unstiffened plate) increases. This is because the ratio of the energy consumed in bulging to that consumed in shearing reduces as the plate thickness increases as reported in refs. [16 and 17]. Therefore, the use of a stiffener becomes more appreciable when used with a thin plate.

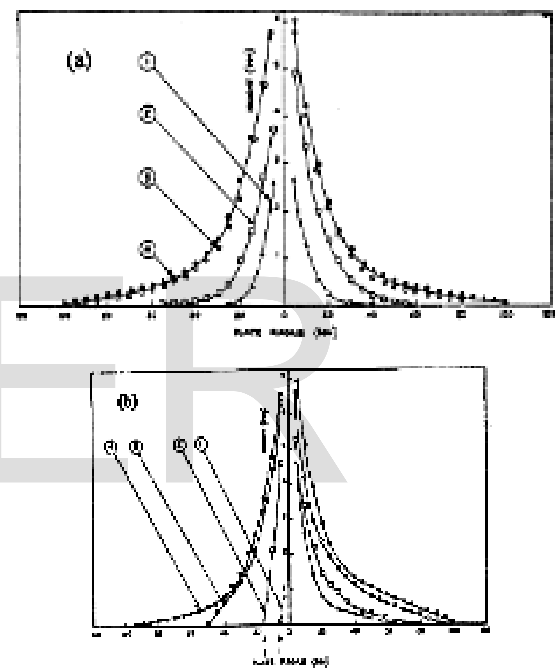


Fig. 3. Profiles of 1.5 mm thick mild steel plate at containment where profiles identified 1, 2 and 3 refer to the conditions with the stiffener at 5, 15, and 50 mm from the center of the plate respectively and profile number 4 refers to a plate without stiffener in the directions (a0 parallel to and (b) perpendicular to the stiffener axis

On the whole, it can be concluded that reinforcing thin plates or shield –bumper- reduces its effectiveness in resisting perforation by high speed projectile. The reduction in effectiveness is higher with thinner shields and the nearer the stiffener to the center of impact. Therefore, if stiffening of a thin shield is required, it should be provided by increase of its thickness, and under no circumstances by providing a local member as a bracket, web, flange or beam. Recently, systems utilizing the plastic behavior of materials are used as means of protection from the dynamic loads by absorbing or dissipating the force and energy produced in some way to protect or re-

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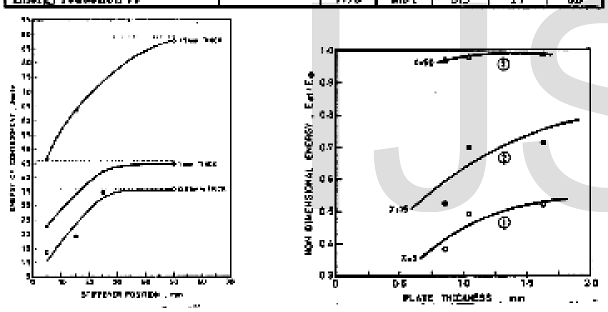
duce the damages. The development and design of mechanical devices or systems for protection against the effects of dynamic loads has become increasingly more important to all engineers in general and to civil, architectural and mechanical engineers in particular, especially with the advances in technology which have led to higher speeds and more massive automobiles and aircrafts, [26]. The ideal situation for the devices or systems to deal with the forces and energies is to interact such that most of the force and energy should be absorbed before reach the object. The interaction between these protection devices or systems in a way that the provision of maximum protection should be the fundamental principle upon which the members should be based. Although different systems have been developed and used for protection from the damages including those reported by the author. There still a great demand for research to improve the existing systems and develop new more effective systems. Therefore, an enormous amount of research works, both experimental and theoretical, were carried out [28-40]. A recent review on the subject is given in refs. [39 and 40]. The main objective of their research work was to protect the members from severe damage.

Distance of stiffener from center of impact, mm	No Stiffener	50	40	25	15	5
Velocity of containment, m/s	57	56.44	56.28	56.05	41.33	35.14
Energy of containment, Joule	35.85	35.15	34.95	34.67	18.85	13.63
Energy reduction %	-	1.95	2.51	3.3	17	62



(A) (B)

Fig. 4. (A) Effect of stiffener position on energy of containment for 0.85 and 1.5 mm thick; (B) Non- dimensional energy versus plate thickness, where curves 1,2 and 3 refer to stiffener position at 5, 15, and 50 mm from the plate center.

Recently, systems utilizing the plastic behavior of materials are used as means of protection from the dynamic loads by absorbing or dissipating the force and energy produced in some way to protect or reduce the damages. The development and design of mechanical devices or systems for protection against the effects of dynamic loads has become increasingly more important to all engineers in general and to civil, architectural and mechanical engineers in particular, especially with the advances in technology which have led to higher speeds and more massive automobiles and aircrafts, [26]. The ideal situation for the devices or systems to deal with the forces and energies is to interact such that most of the force and energy should be absorbed before reach the object. The interaction between these protection devices or systems in a way that the provision of maximum protection should be the fundamental principle upon which the members should be based. Although different systems have been developed and used for protection from the damages including those reported by the author. There still a great demand for research to improve the existing systems and develop new more effective systems. Therefore, an enormous amount of research works, both experimental and theoretical, were carried out [28-40]. A recent review on the subject is given in refs. [39 and 40]. The main objective of their research work was to protect the members from severe damage.

5 SYSTEMS UTILIZING THE PLASTIC DEFORMATION FOR PROTECTION

For such systems the material which possesses high ductility at high rate of strain will be advantageous. Such materials are the superplastic materials. Super plasticity is the phenomenon in which the material deforms to large strains at low stress under certain conditions of temperature and strain rate. These conditions are:

1) The forming temperature around half the absolute melting temperature.

2) Very low strain rate within the range from 10-2- 10-4/s.

3) The grain size will be less than 10μm; referred to it as micro-grain super plasticity.

4) The tensile elongation can reach more than 2000%.

These materials are sensitive to strain rate and possess extra ordinary high ductility. The utilization of superplastic tin-lead alloy was used as an alternative material to replace the previously used ordinary engineering materials which is in addition to being superplastic at room temperature, it has the advantage of being rate sensitive at very low strain rates ranging from 1×10-2 to 1/s. [14]. Different protection systems using this superplastic material were designed, manufactured, tested and reported by the author in ref., [41].

6 NEW SUGGESTED SYSTEMS FOR PROTECTION

6.1 Utilization of Severe Plastic Deformation Method

Severe plastic deformation processes are recent forming methods which are used to obtain fine and ultra-fine structure in metals and their alloys. The mostly used process among these processes is the equal angular channel pressing method, known as ,ECAP, .This system is designed, manufactured and reprted by the author, []. The system is under testing and the obtained results are promising. They will be published with the results of the other suggested systems in due course

1. Single Plate Shield
a). Un-backed
b). Backed with water
c) Backed with other materials
2. Laminated Plate Shield
a) Without separation.
b). With separation i.e With standoff distance.
3). Multi Plate Shield

4 CONCLUSION

The following points are concluded:

1. The previous used methods and systems in protecting

structural members from damage are given and discussed

2. Utilization of superplastic materials to replace the traditional engineering materials is given and discussed.

3. New suggested alternative systems for protection are also given and discussed. These include: backed and un-backed single sheet, laminated plate shields, design engineers and multi plate shields.

4. The utilization of heavy plastic deformation ECAP is pointed and discussed.

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