Hyper Velocity Impact Phenomenon and the Damages Caused by it to Structural Members

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Abstract: - Impact conditions involve velocities below the sonic speed, which is normally of the order few hundreds up to thousand m/s, whereas the hypervelocity impact applies for conditions of impact with velocities higher than the acoustic speed of either the impacting object or the impacted target. The velocity at this condition is few thousands m/s and much higher. The effects of hypervelocity impact depend on projectile and target materials, impact velocity, incident angle and the mass and shape of the projectile impacting head. In hypervelocity impact, the projectile velocity exceeds the speed of sound within the target material. The resulting shock wave that propagates across the material is reflected by the surfaces of the target, and reverses its direction of travel. The superimposition of progressing and reflected waves can lead to local stress levels that exceed the material's strength, thus causing cracks and/or the separation of spalls at significant velocities. At low impact velocities, plastic deformation normally prevails. With increasing velocities the projectile will leave a crater in the target. Beyond 4 km/second (depending on the materials), an impact will lead to a complete break-up and melting of the projectile, and an ejection of crater material to a depth of typically two to five times the diameter of the projectile. With decreasing target thickness, the effects range from cratering, via internal cracks, to spall detachment, and finally to plug formation. To avoid the damages caused by the hyper velocity impact phenomenon, it is essential to define and design effective protection measures to protect all structures and their members from the damages particularly aircrafts and space vehicles which are liable to be subjected to such conditions. In this paper, damages caused by this ypes of impact which include: metallurgical changes, scabbing and incipient scabbing, crater formation and fractures are presented and discussed.

Key-Words: - Damages, Hypervelocity Impact, Aircrafts, Space vehicles

1 Introduction

Penetration of a target plate implies the entrance of the projectile into it without completing its passage through it. On the other hand perforation implies the complete piercing of the target by the projectile and completes its passage through it, while still has some remaining velocity, [1].Containment is a term refers to the condition when the projectile perforates completely the target but still retained in it which defines the limiting condition or the criterion for shielding against the damage. Impact of projectiles on target plates involves velocities well below the sonic speed of either the projectile or the target plate. The impact twhereashyp The author of [2] defines. Based on the impact velocity of thee projectile three ranges of impact velocity with different failure modes were presented in, [2]. In the range of velocities under 250 m/s, local deformations and penetration of the test specimen are related to its global deformations. The load carrying behavior of the complete structural part is activated. On average with velocities between 0.5 and 2.0 km/s, impact principally leads to local effects. The material reaction in the impact zone can be described by a wave theory. The diameter of the impact zone is about three times the diameter of the projectile [2].

Higher velocities of the projectile might cause vaporization of the materials. The situations in which hypervelocity are: in the use of the electron beam, the laser and in explosive welding. In its most arresting form, however, Hyper-velocity impact has been widely studied because it is a phenomenon associated with several industrial and engineering applications, for example: in the impact of meteorite, : in the use of the electron beam, the laser and in explosive welding, perforation and cutting by high explosive shaped charge. In its most arresting form, however, it is often connected with ablation, but this is not encountered in this paper. The speed of meteorites ranges from 11 to 80 km/.s., whilst that of scientific satellites is about 8 km/s relative to the speed of the earth' ; a very obvious instance of the application of hypervelocity impact knowledge is needed then in considering the collision of meteorites with the skins of satellites. Plasticine was much used for metal-deformation studies because it is a convenient model which will demonstrate patterns of flow and give indications of how force and energy requirements are affected by speed, it was used in [35] for investigating the hypervelocity phenomenon. Many papers have been written on the subject of hypervelocity impact, but no attempt will be made to review these here. The readers are referred to the work reported in [37], to the book by Rinehart and Pearson' which summarizes the phenomena and the empirical results of various research workers in this field,[38] and to the survey of the structural effects of impact, [39] and to the recent paper by Eichelberger, [40]. These four references can be consulted for much of the background work connected with the phenomena. A definition of hypervelocity impact has been provided by Eichelberger as: "A hypervelocity impact is one in which the initial velocity exceeds that necessary to produce steady state pressures greater by an order of magnitude than the yield strength of both the target material and the projectile." This is the physical situation with which the authors are concerned principally. When the projectile and target are of the same material we may express the above definition to some degree numerically, by defining a number pxV^2/4Y; if the steady-state theory of hypervelocity impact due to Birkhoff et al. and Pack and Evans' is accepted, then in these circumstances, the steady-state pressure generated is pV2/4, for identical projectile and target materials. The value to be ascribed to Y in any given hypervelocity circumstance is scarcely ever discussed; in fact its value is uncertain, because it is a function of both strain-rate and temperature. It is not clear whether the "static" yield stress value (as obtained in a simple compression test at a strain-rate of 10-'/sec) should be used in this expression or whether it should be the quantity at the strain-rate at which the impact takes place. If the latter was to be the case, then it would be difficult to know how to find the yield stress and the rate of strain applicable, always supposing, of course, that strain-rate has a meaning in hypervelocity situations “of projectile and target material, impact velocity, incident angle and the mass and shape of the projectile. In hypervelocity impacts, the projectile velocity exceeds the speed of sound within the target material. The resulting shock wave that propagates across the material is reflected by the surfaces of the target, and reverses its direction of travel. The superimposition of progressing and reflected waves can lead to local stress levels that exceed the material's strength, thus causing cracks and/or the separation of spalls at significant velocities. At low impact velocities, plastic deformation normally prevails. With increasing velocities the projectile will leave a crater in the target. Beyond 4 km/second (depending on the materials), an impact will lead to a complete break-up and melting of the projectile and target materials. Furthermore, an ejection of crater material to a depth of two to five times the diameter of the projectile. However, with decreasing target thickness, the effects range from cratering, via internal cracks, to spall detachment, and finally to clear hole perforations. A series of four papers were published in [40], dealing with experimental observations of dynamic crack propagation in thin, large sheets of a Homalite 100 plastic material which allow simulation of crack growth in unbounded plates. In the first paper crack initiation resulting from stress wave loading was examined as well as crack arrest. It was found that for increasing rates of loading in the microsecond range the stress intensity factor required for initiation rises markedly. Crack arrest occurs abruptly without any deceleration phase at a stress intensity lower than that which causes initiation under quasi-static loading. In the second paper he analyzed the occurrence of micro cracks at the front of the running main crack which control the rate of crack growth. The micro cracks are recorded by real time photography. By the same means it is shown that these micro cracks grow and turn away smoothly from the direction of the main crack in the process of branching. The third paper questions the existence of a unique relation between the instantaneous stress intensity factor and the instantaneous crack speed. It was shown that the crack propagates with constant velocity from the instant of initiation, even though the stress intensity factor varies considerably during crack propagation. The limiting crack speed is viewed as a consequence of crack tip micro-fracturing discussed in the second paper of the series. The crack branching is considered as a natural evolution of the micro fracturing process with certain statistical features. In this last paper he examined the effect of stress waves impinging on the tip of a running crack. The stress waves are induced by (a) reflection from the boundary through a judicious choice of specimen geometry and (b) through use of a second stress wave generator. It is found that these waves affect the direction of propagation, the crack speed, and the process of branching. However, we conclude that while stress waves modify the process of crack branching they do not by themselves constitute the reason for crack branching. Also, it is demonstrated how wave reflections in small specimens may complicate the dynamic crack propagation behavior and thereby the interpretation of result. Addition to the aforementioned structural damage, hypervelocity impact typically creates plasma that can lead to the electromagnetic interference. In addition, when the spacecraft surfaces are already electrically charged by the surrounding aerodynamic plasma, the impact-induced plasma can give rise to substantial electrical discharges, which can result in a major structural damage to the spacecraft. Other impact-induced effects include the generation of light flashes and the attitude changes in the spacecraft. The extent of structural damage caused by hypervelocity impacts depends on a number of parameters associated with the impactor (a meteoroid or a space-debris particle) and the target (the outer skin of the spacecraft).

I. DAMAGES CAUSED BY HYPERVELOCITY IMPACT

As mentioned in the abstract of the paper, impact of projectiles on target plates involves velocities well below the sonic speed of either the projectile or the target plate Zukas defines three ranges of impact velocity with different failure modes. In the range of velocities below 250 m/s, local deformations and penetration of the test specimen are related to its global deformations. The load carrying behavior of the complete structural part is activated. On average with velocities between 0,5 and 2,0 km/s, impact principally leads to local effects.

Figure 14: A typical thick plate with the crater formed at the top caused by a spherical projectile which is embedded in the bottom of the crater and a single scab detached from the rear end due to the reflected tensile wave.

The material reaction in the impact zone can be described by a wave theory. The diameter of the impact zone is about three times the diameter of the projectile [2]. This range of velocities has been investigated in this research paper. Higher velocities of the projectile might cause vaporization of the materials.

Fig.15: A single scab at the end of the Cutting jet from a lined cavity shaped charge

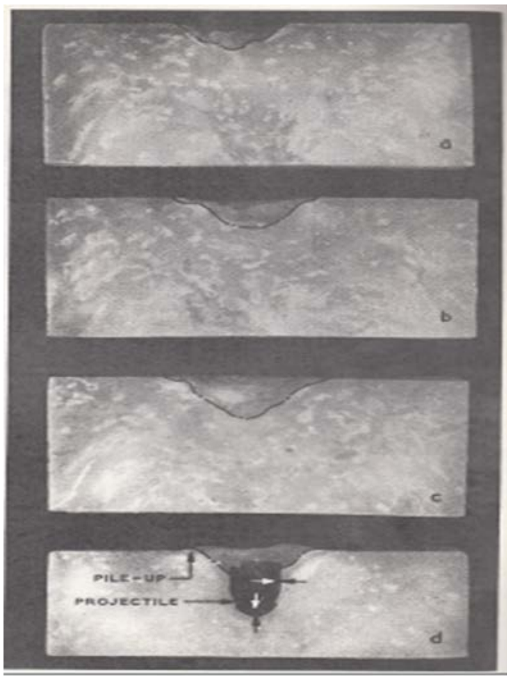

Fig.16: Typical sectioned wax targets, where the velocity and the length of the projectile in (a) to (d) were 2330, 1940, 1835 and 1667 ft/sec [35].

3 STRUCTURAL PROTECTION SHIELDS

double-layer protection Giotto in 1985, with Whipple shield at bottom, protection is achieved through Whipple shields with aluminum and Nextel-Kevlar bumper layers. The shields are composed of an external, thin bumper shield that is exposed to the debris flux and causes the projectile to completely disintegrate during impact. The resulting cloud of liquid projectile and target material that forms behind the bumper leads to a much wider spatial and temporal distribution of momentum, allowing the back wall of the shield to withstand the impact pressure. Today, these shields have reached a mature state of development. In the last three decades, high strength concrete (HSC) has been dominated as a material for special use in high-rise buildings, offshore structures and bridges. However HSC is characterized not only by its high compressive strength, but also by other properties such as low permeability and reduced shrinkage effects. The properties of HSC indicate, that it must be a well-suited material for protection against impact loading with high dynamic effects. The behavior of slabs made of HSC has been investigated in a research project reported in refs.[41and42]. The aim of the project was the development of materials and structures which can resist high dynamic loading. Several barriers made of different admixtures were tested under gun fire with a maximum velocity of 890 m/s. The tested barriers, with an element size of 50x50 cm and of various thicknesses, did not contain reinforcement bars. This paper presents different failure modes such as penetration, and scabbing of the barriers made of different admixtures. The experimental studies with different thicknesses of slabs of HSC show clearly that resistance against impact loading not only depends on the uniaxial compressive strength. Concrete mixtures with almost the same compressive strength but with different types of aggregate showed different behavior. Mixtures with hard aggregate like quartzite and basalt had a higher resistance against impact than the slabs containing limestone aggregate. Concrete mixtures with short steel fibers showed an optimal compromise between workability, improved ductility and protection against impact. The additional use of polypropylene fibers lead to a higher ductility of the concrete slabs. The tensile strength could be increased so that the scabbing damages at the rear side, caused by the reflection of the tensile wave, were significantly reduced. A broad range of parameters have been investigated experimentally. Recently, with the consequence of the global political developments during recent years, this puts multiple demands on researches now more than ever to develop new materials and protection systems for structures and people against damages caused by projectile impact and hypervelocity impact phenomena, particularly with the increase of the terrorist acts, taking into consideration that the protection system must be both effective and economical and the materials and components used with it should be available in the region where they are going to be used. Hence, the idea of using elements of high strength concrete (HSC) was born as an alternative to the available protection system made of steel elements by different military establishments over the world. e.g. the research project which was initiated in the research project reported in [41]. The aim of the research project was the development of concrete mixtures with high compressive strength, a high strength of mortar matrix and an optimized connection between mortar and aggregate. Additionally, basic research about the material behavior of high strength concrete under impact loading with extremely high strain rates has been carried out. Based on the composition of the light inter-metallic compounds; a broad range of parameters have been investigated experimentally. Also in their research, the behavior of slabs made of HSC has been investigated. Several barriers made of different admixtures were tested under gun fire with a maximum velocity of 890 m/s. The tested barriers, with an element size of 50x50 cm and of various thicknesses, did not contain reinforcement bars. Furthermore, different failure modes such as penetration and scabbing of the barriers made of different admixtures were investigated. The experimental studies with different thicknesses of slabs of HSC show clearly that resistance against impact loading not only depends on the uniaxial compressive strength. Concrete mixtures with almost the same compressive strength but with different types of aggregate showed different behavior. Mixtures with hard aggregate like quartzite and basalt had a higher resistance against impact than the slabs containing limestone aggregate. Concrete mixtures with short steel fibers showed an optimal compromise between workability, improved ductility and protection against dynamic loading. Today, ESA's impact protection research activities concentrate on quantifying the expected failure rates and failure characteristics of unmanned spacecraft due to space debris and meteoroid impacts. The aim is to reduce the design margins required for no structural perforation, as required by manned modules. Material models for composite materials under very high strain rates have been developed for Nextel and Kevlar. These models have been used to verify the structural protection of several ESA spacecraft, including Columbus and ATV. ESA's space projects use damage assessment tools in combination with debris and meteoroid environment models to predict potential damage from hypervelocity impacts, and to define effective protection measures through shielding and design. Smaller, objects can only be defeated by passive protection techniques, as used with the International Space Station (ISS). As required by manned modules. More recently, resistance to hypervelocity impact using reinforced carbon-carbon/ carbon-foam thermal protection systems was investigated using two-ply panels. The outer panel is made of a carbon-carbon composite while the inner ply is constructed from a carbon-based foam. The authors carried out a transient non-linear-dynamics based analysis in order to predict the extent of damage and probability for failure of the carbon-carbon/ carbon-foam common aero vehicles,(CAV), panels during hypervelocity impact of space debris with the outer surface of the CAVs. They found that despite its relatively low strength, the carbon-foam can provide a major increase in the resistance of the CAV panels towards penetration of the hypervelocity debris particles, [43].

3 Different Systems for Shielding from Damages caused by Hypervelocity Impact

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) Other Alternative Systems; replacing the traditional engineering materials by superplastic, ceramic, composite, fiber-reinforced materials.
5) Utilizing the Severe Plastic Deformation Processes, SPD, e.g. Equal channel angular pressing, (ECAP).

4 Conclusion

From the work in this paper the following points are concluded:
i) The hypervelocity impact phenomenon is reviewed and discussed.
ii) Some of the damages caused by the phenomenon together with some protection systems are also presented and discussed.
iii) Despite the large number of published papers, the subject is far from being complete and further work is still required.

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References:

[1] W. Goldsmith, Impact, Arnold, London, 1960.

[2] J. S. Zukas, T. Nicholas, H.F. Swift, L.B. Greszczuk, D.R.Curran, Impact Dynamics, John Wiley and sons Inc.,9,1982.
[3] W. Johnson, Impact Strength of Materials, Arnold, London, 1972.
[4] G. I. Taylor, The Use of Flat Ended Projectile for Determining Dynamic Yield Stress, 1: Theoretical Considerations, Proc. R. Soc., A.194(1948) 289.
[5] B. Robins, New Principles of Gunnery, London,1742.
[6] L. Euler, Neue Grundsatze der Artillerie, Berlin, 1745.
[7] J. V. Poncelet, Icours de Mechanique Industrielle, 1829.
[8] J. V. Poncelet, Introduction la Mechanique Industrielle, Bruzelles, 2nd Ed, 1835.
[9] J. V. Poncelet, Mem. Acad. d'sciences, 15(1835) 55.
[10] Z. Bashforth, Motion of Projectiles, Asher, London, 1873.
[11] M. Gildmester, H. Strehl, Ann. Phys. Lpz., 18(1905)567.
[12] W. Bauer, Ann. Phys. Lpz., 80(1926)232.
[13] H. A. Bethe, Attempt of a theory of armour penetration, RARDE Report No. R52/1203/3, May (1941).
[14] G.I. Taylor, Quart. J. Mech. and App. Math., 1(1948) .
[15] T.W. Thomson, J. App. Phys. Vol. 26 (1955) 80.
[16] W. Freiberger, Proc. Cambridge Phil. Soc. 48(1952)135.
[17] G. I. Taylor, H.A. IINotes, Pethe's theory of armour penetration, Min. of Home Security, Defence Res. Committee, Report No. RC280, 1941.
[18] A.V.J. Masket, App. Phys., 20(1949)132.
[19] J.L. Bluhm, Proc.Soc. Exp., Stress Analysis, XIII, 1956, pp. 167.
[20] W.T. Thomson, J. App. Phys., 26(1955) 80.
[21] M.S. Sodha, V.K.J JAIN, Applied Physics: letters to the editor.
[22] M. Zaid , B. Paul, J. Frank Inst. 264(1957) 117.
[23] B. Paul, M. Lid, J. Frank Inst., 265(1958) 317.
[24] M. Zaid, B. Paul, J. Frank Inst., 268 (1959) 24.
[25] R.F. Racht., T.W. Ipson, J. App. Mech., 30(1963) 384.
[26] R.L. Jameson, J.S. Williams, Velocity losses of cylindrical steel projectiles perforating mild steel plates, BRL Report No. 1019, 1957.
[27] K.E. Spells, Proc. Phys. Soc., 64, No. 375B,1951, pp. 212. 28. Nishiwaki J., J. Phys. Soc. Japan, Vol.6(1951) 374.
[28] R. Sutterlin , Mem. de l'artill, France, 96, 18.
[29] F.A. Bahshian, Inst. Mech. Acad. Sci., USSR, Ap. Math. And mech. XII, 1,1948.
[30] P.C. Chou, Development in Mech., 1, 1961.
[31] R.G. Thomson, Analysis of hypervelocity perforation of a visco-plastic solid including the effects of target-material yield strength, NASA Report No. TR-R211,1965.
[32] W. Goldsmith, T.W. LIU, S. Chulay, Exp. Mechanics, Vol.5(1965)385.
[33] A.I.O. Zaid, A Simple Model for the Perforation of a Flat Plate by a High Speed Flat-Ended Cylindrical Projectile, 6th Cairo University International Conference on Mechanical Design and Production, MDP-6, Cairo-Egypt, 2nd -4th Jan., 1996, pp. 173.
[34] W. Johnson, F.W. Travis, and , S.Y. Loh, High speed cratering in wax and plasticine, Int. J.Mech.Sci. Vol.10(1968)593-605.
[35] H.G. Hopkins and H. Kolsky, Proc. 4th Symp. Hypervelocity Impact, (edited by A.S.Gallbraith), Elgin Air Force Base, Florida, Paper No.12, 1960.
[36] J.S. Rinehart and J. Pearson, Behaviour of Metals Under Impulsive Load, Dover Publications, New York, 1953.
[37] M. Kornhauser, Structural Effects of Impact, Cleaver-Hume Press, London,1964.
[38] R.J. Eichelberger, Behviour of Materials under Impulsive Loading, Amer. Soc. Mech. Eng, 1955, pp.155
[39] W. G. Knauss, An experimental investigation into dynamic fracture: IV. On the interaction of stress waves, International Journal of Fracture November, Vol. 26(1984)189-200.
[40] I. Abdul Rahman, A. Mujahid, A. Zaidi, Q.B. Latif, Review on empirical effects of hard missile on concrete structures, International J. of Sustainable Construction Engineering and Technology, (2007)73-97.
[41] A. kustermann, M. Keuser, Influence of material properties on the penetration process in high strength concrete (HSC), The 11th International Symposium on Interaction of Effects on Munition with Structures, 2002.
[42] M. Grujicic, B. Pandurangan, C.L. Zhao, S.B. Biggers, D.R. Morgan, Hypervelocity impact resistance of reinforced carbon-carbon/carbon-foam thermal protection system, Applied Surface Science, Elsevier 2005