Stress Waves in Solids, Transmission, Reflection and Interaction and Fractures Caused by Them: State of the Art

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Abstract: - Stresses caused from Intermediate rate and dynamic rate loading having strain rates in the range 10 to 10000 /s are transmitted in solids by elastic stress waves. Two types of these waves exist either longitudinal or torsional. The longitudinal stress waves transmit tensile and compressive stresses with speed $Cl = (E/\rho)^{1/2}$, which equals the acoustic speed, whereas the torsional waves transmit shear stresses with speed $Ct = (G/\rho)^{1/2}$, where E is the modulus of elasticity, ρ is the density, and G is the modulus of rigidity of the solid material. In this paper, stress wave propagation in solids using the well established Rayleigh acoustic equations are given and discussed. This includes the transmission, reflection and interaction of the stress waves. The useful applications of these waves are presented and discussed. A new theoretical model based on approximating the conical rod into semi-infinite number of steps is developed for investigating the history of a dynamic compressive stress pulse impinging at its large end. The amplification of the stress level during its transmission and reflection is given and discussed.

Key-Words: -Stress waves, Compressive stress, Transmission, Reflection, Interaction, Fracture, Conical rod.

1 Historical considerations

Although as early as 1889,Rayleigh recognized the existence of sound waves, stress waves which are governed by similar equations and speeds as acoustic waves have not been introduced until 1907 by Sears[1], who presented results of tests where he used the recorded instant of separation(under the reflection of stress wave) of two ballistically supported bars, under axial impact to determine the sonic velocity of the bar material, [1]. Later, Hopkinson, [2-4] has given special consideration to the interaction of incident and reflected waves and described a simple technique whereby he was able to measure both the duration of a blow and the maximum pressure developed by it. Thereafter his apparatus was further developed and used to establish the general form of an incident compressive pulse caused by impact of a high speed projectile or from an explosive charge and to investigate the behavior of materials under high strain rates, and ever since was known as Hopkinson pressure bar. Later, the subject was investigated in detailed form by Kolsky in 1953, [5]. However, the utilization of stress waves in engineering applications seems to have started in early 1960s by the development of high energy rate forming (HERF) processes and the uprising of space vehicles and later for determining the mechanical properties of materials under intermediate and high strain rate loading. Tsui, 1968, Kinslow, 1970 and Zaid, 1977. In quasi-static loading where the involved strain rates range from 0.0001/s to 1/s and the time involved varies from seconds to months and even more. In these systems some of the 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 100/s in the first and from 100 to 10000/s in the latter, and the time involved in these systems is of 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 before other parts are not reached or felt by the impulse load. The intermediate rate and high strain rate stresses caused by their corresponding loading systems may be either tensile, compressive or shear are transmitted through a solid by waves referred to as stress waves. The published work on stress waves is voluminous and well documented in the literature attempting to understand the mechanics of their propagation and interaction in solid members of various shapes, [1-5]. These include mechanical parts used in automobile, aircraft, space vehicles, dies in high energy rate forming processes, [HERF], and the investigation of the mechanical behavior of materials under dynamic and shock loading conditions using the Hopkinson and modified split Hopkinson pressure bar under compression, tension and torsional loading. The propagation of a longitudinal compressive stress pulse has been considered by Landon and Quinney, [6] who employed such a bar to measure the pressure produced by detonation of the explosive at its large end. He deduced a mathematical expression for determining the momentum associated with the pulse. He found that the momentum decreases in magnitude as the pulse approaches the apex. Several attempts have been made in the past to investigate the effects associated with stress waves in rods of varying cross section, [5-9], and in multi-layered plates, [10, 11]. 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 designed systems. These newly developed materials are now widely used due to their superior properties of high strength to weight, high ductility,...etc. A need for implementing them into practical use has arisen. Because of their favorable features, they have great potential in manufacturing many industrial and engineering parts. However, an adherent gap exists between the research and industrial field to push these materials into usage. For newly produced materials to be shaped and formed into their final shape and become traditionally used further research is required. In the last decades, industry in general and researchers, including the author of the paper, began showing interest in these newly developed materials. Due to the wide scope of the subject and the limited space and the number of pages allowed for, only part of the large number of publications is referred to. Therefore, I apologize for authors whose research work was not referred to. The dynamic tensile and compressive stresses travel through a solid media by a longitudinal stress wave with a velocity equals to the acoustic speed in the solid, Cl = (E/ ρ)1/2Where E and p are the modulus of elasticity and the density of the solid respectively, however the dynamic shear stresses are transmitted through the solid media by a shear velocity Ct which equals (G/ ρ)1/2.Where G and P are the modulus of rigidity and density of the sold respectively. It is worth mentioning that Ct is less than ½ Cl. Table 1 gives the longitudinal wave speeds, Cl of some materials.

Table 1. The longitudinal wave speed, Cl , and shear wave speed, Ct, 0f some metals,[7]

Metal	Cast iron	Carbon steel	brass	Cu	Lead	Al
E N/m2	$114*10^9$	$204 *10^9$	$93.3 *10^9$	$114*10^9$	$17.6*10^9$	$69*10^9$
$\rho_=$ Kg/m^3	$0.72*10^4$	$0.775*10^4$	$0.83 *10^4$	$0.887*10^4$		
CL= $(E/\rho)^{.1/2}$ m/s g = 9.81 m/s2	3980	5150	3360	3690	1190	5100
Ct=$(G/\rho)^{-1/2}$ m/s	2470	3230	2040	2290	700	3100

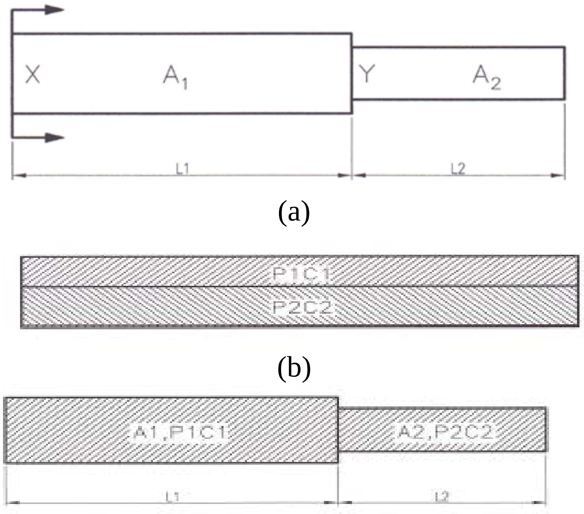
In this paper, concentration is given to the beneficial usage of stress waves and the damages caused by them in addition to the avoidance of their occurrence.

2 Literature review

Although sound waves has been recognized by Rayleigh [14], stress waves which are governed by similar equations and speeds as acoustic waves have not been seen introduced until 1953 by Kolsky[15]. However, the utilization of stress waves in engineering applications seems to have started in the late 1960 by the development of high energy rate forming (HERF) process and the uprising of space vehicles [16, 17, 18]. Abbott and Broutman conducted experiments in studying the one dimensional stress wave propagation in a freely supported prismatic bar. They obtained some observations on phenomena of longitudinal stress wave propagation in a filament of reinforced composites [19]. They used surface mounted strain gauges to matches the results determined by the familiar relation $(E/\rho)^{1/2}$. In 1979, Jung, (who served as general engineer at the forest products laboratory, United States department of agriculture), issued a technical report of study that was conducted to compare stress wave devices and determine the information on available from stress waves in veneer sheets. He found that the stress wave is distorted as it passes a defect which indicates that an estimate of the location and size of the defect can be obtained but with loss of information regarding wood quality in the areas immediately behind a knot [22]. Cetinkaya and Vakakis analyzed the transient response of finite biperriodic layered structures under axi-symmetric loading conditions using a double integral transform technique. They found that the transient waves are localized close to the area where the load is applied. Furthermore, as the coupling between the layers increase the transmission of stress waves through the layered medium is enhanced and stress localization diminishes. They also found that the weak coupling between layers affects the distribution of the shear stress than that of the longitudinal stress field [23]. Zaid investigated the effect of stress wave s in a conical bar due to a single incident compressive square pulse. He developed a computer program which calculates the transmitted and reflected pulses together with their interaction at any section along the bar. The analysis of his results showed that there is an amplification of the amplitude of the stress as the stress wave proceeds towards the apex of the bar. Furthermore, the compressive incident stress has developed a tensile stress lagging behind it [24]. Analytical and computational studies of the stresses and displacements in functionality graded materials (FGM) when subjected to quasi-static loading were carried out by Suresh and Mortensen [25, 26, 27] . They showed that the optimization of the structures and geometry of the graded interface between the two dissimilar layers resulted in reducing the stress levels significantly. Hasco't numerically solved the propagation of a shock wave in a chain of elastic beads without restoring forces under traction. They found a sequence o peaks of decreasing amplitude and velocity and by analyzing the main peak at different times were able to confirm a recently proposed scaling law for its decay [28]. The response of plates made of metallic ceramic in two dimensions was investigated by Li [29] and response of such plates under the effect of impact in three dimensions was numerically investigated by Han [30]. In their research study, the FGM is approximated to a multi-layered structure and the material properties of each layer were assumed to be constant. Following the work of some of the previous authors and using a stress pulse of wave length equal to the plate thickness, Berezovaki investigated the effect of two dimensional elastic stress wave propagation in layered and graded metal-ceramic plates. They considered two distinct models of FGM and numerically simulated each of the two models. They found that the size, shape, clustering, and in homogeneities in the random distribution of embedded reinforcement particles may affect the results of simulation of the model they proposed [31]. Twofighi investigated the elastic wave propagation in the circumferential direction of anisotropic cylindrical curved plates. They used a technique based on fourier series expansion of the unknown quantities to facilitate solving the wave propagation problem [33]. Berezovski numerically studied the propagation of stress waves in FGMs using a composite wave-propagation algorithm with two distinct models of FGMs. They concluded that the model of FGM without averaging of material properties can give more detailed information about the dynamic behavior of chosen structure. They also proposed using this information for the nondestructive evaluation of material properties [32]. Long investigated the causes of shot to shot dispersion in rifles. He discovered that optimum loads (charge, seating depth) work across multiple rifles having different barrel lengths. To explain why, he proposed a model relation rifle internal ballistics, longitudinal shock waves, and shot dispersion. He assumes that the pressure pulse from the gases in the chamber cause a traveling wave of stress that bounces back and forth along the barrel, slightly changing the bore diameter in the process. Minimum dispersion of the shots results when the rate of change of the bore diameter is minimum, and this dispersion presents the least sensitivity to load variation. He also found that the position of this wave and its effect on the muzzle at the point of bullet exit is cause of the majority of the dispersion around the mean point impact [34]. He discussed the stress waves created following primary cracking which may cause further fractures in components in high temperature reactors that can be subjected to both thermal and mechanical loading. It can cause them to fracture in unstable manner if the material is initially brittle or becomes so through irradiation imbrutement. They carried out a dynamic analysis of the stress waves in cylindrical specimens fractured as a result of applying a thermal load. The analysis has been carried out using finite element method. Effects of the propagation speed of the primary crack have been considered and the assumption of uniform crack speed has been assessed [35]. Tasedemirics sponsored by the U.S army research laboratory, investigated the case of multilayer materials consisting of ceramic and glass/epoxy with a rubber interlayer subjected to a high strain rate compression using a split-Hopkinson pressure bar (SHPB). The feasibility of modeling stress wave propagation in complex multilayer materials has been demonstrated. They have shown that the effects of lateral confinement of a normally low-modulus interlayer material can affect the response wave propagation significantly [36]. Xu and Rosaki carried out an experimental investigation of the generation and subsequent evolution of impact damage in heterogeneous two layered materials, one is a polymer layer which bonded to a second metallic layer when subjected to impact loading. High speed photography and dynamic photo elasticity were utilized to visualize the nature and sequence of dynamic failure modes. they found that the interlayer crack growth was the dominant dynamic failure mode taking place inside the weak layer[37]. Gebbeken and Greulich developed a three dimensional dynamic model to investigate the stress wave propagation in a reinforced concrete bar. As they expected, the mechanical behavior was characterized by cracking of the concrete. The relative displacement between the concrete and the reinforcement were taken into consideration both in the direction parallel to the bar and in the perpendicular direction[38]. Sharma investigated the effect of initial stresses on the reflection of stress waves at the free surface of the medium. He found that the effect of the initial stress on the reflected waves varies with the direction on the incident wave. The elastic properties, and the anisotropy present in the material. However, he concluded that the effect of the initial stress on the phase directions of the reflected waves is negligible and that it has a very small effect on the phase velocity of the reflected waves[39]. Zhange and Batra studied the elastic wave propagation in FMGs using modified smoothed particle hydrodynamics (MSPH) method. They showed that for the same placement of particles, the MSPH method gave better results than the finite element method. They also found that the initial smoothing length in the MSPH method is 1.1 times the distance between two adjacent particles [40]. In 2007, Grady, D.E., on behave of applied science research assistances, Inc. prepared a report for US Army TARDEC-Emerging Technologies Team. The report covered the analysis of shock and high rate for ceramic. It concluded that ceramic demonstrated considerable success as barrier material in armor applications [40].

2.1 Theoretical considerations of stress waves

In this section, the theoretical aspects of longitudinal stress waves, both compressive and tensile which includes their transmission, reflection and interaction are presented and discussed. If a dynamic tensile or compressive stress pulse of intensity 6I impinges on an elastic solid, it will be transmitted through the elastic solid with a longitudinal stress wave having a speed $Cl=(E/\rho)^{1/2}$ without change in sign or magnitude unless it meets a stress discontinuity defined as a change in cross sectional area or acoustic impedance, ρ.C or both, Figs. 1(a), (b), and (c) respectively. In this case it will be partially transmitted, σ_T, and partially reflected, 6R. The values of σ_T and σ_T are determined from equations 1 and 2 respectively as follows:



(a)

(b)

(c)

Fig.1: Different cases of stress discontinuity.

Consider the force equilibrium at the plane of discontinuity AB.

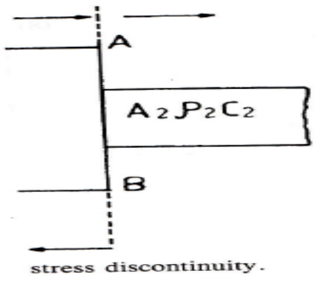


Fig.2: A Stress discontinuity

Force equilibrium gives:

$(\sigma_I+\sigma_R)A_1=\sigma_T A_2$ (1)

And continuity of particle velocity gives:

$V_I-V_R=V_T$ (2)

The elementary theory of stress wave propagation gives [5, 9];

$\sigma=\rho CV$ (3)

where σ is the stress intensity, ρ is the density of the material and C is the longitudinal wave speed of the material, which equals to the acoustic speed of the material equal to (E/ρ)1/2 where E is the modulus of elasticity of material, the term ρc is referred as the acoustic impedance of the material, making use of equation (3) in equation (2) and solving for equation (1) for σ_I and σ_R gives:

$\sigma_T=(2A_1\rho_2C_2/(\rho_1C_1A_1+\rho_2C_2A_2)$ (4)

$\sigma_R=(\rho_2C_2A_2-\rho_1C_1A_1)/(\rho_1C_1A_1+\rho_2)$ (5)

It can be concluded from equation (5) that for a simple change in cross sectional area i.e. when $\rho_{1=}$ ρ_2 and C1=C2, the incident and reflected waves will have the same or opposite signs according to the increase or decrease in size of the cross sectional area. Also the intensity of the transmitted stress falls below or exceeds the intensity of the incident stress. Furthermore, equations (4) and (5),if $\rho_1C_1= \rho_2C_2$ the following points may be concluded:

(a) If $A_2 / A_{1=} 0$, i.e. the end of the rod is effectively free, equation (5) gives $\sigma_{R\,=}$ $-\sigma_{I,}$ and = σ_T = $2\sigma_I\sigma_{T=}$ $2\sigma_{I,}$

(b) If A_2 / $A_1 = \infty$, i.e the end of the rod is effectively fixed, $\sigma_{R\,=}$ $\sigma_{I,}$ and $\sigma_{T\,=}$ 0.These results indicate that a very small shaft attached to the end of one larger in cross sectional area will act as a momentum trap for a pulse or blow on the far end of the large shaft.

$\sigma_T=(2k_1/(1+k1))\sigma_I$ (6)

$\sigma_R=((k_1-1)/(k_1+1))\sigma_I$ (7)

and referred to as the impedance mismatch factor, and if the discontinuity involves ; sectional area, the case of conical rod, then equations (4) and (5are reduced to:

$\sigma_T=(2A_2/(A_1+A_2))\sigma_I=(2k_2/(k_2+1))\sigma_I$ (8)

and $\sigma_{R=}((A_2-A_1)/(A_2+A_1)\ \sigma_I = (1-k_2)/(1+k_2))$ (9)

where $k_2 = A_1/A_2$ i.e. the end of the rod is effectively fixed, $\sigma_{R\,=}$

$\sigma_{T(n-1)} = [\ 2A_n/(A_n+A_{(n-1)})]\ \sigma_I = [2n^2/(n^2+(n-1)^2]\ \sigma_I$ (10)

and the transmitted stress at segment 1 at the apex σ_{T1} is given

$\sigma_{T1}=[2n^2/(n^2+(n-1)^2)*2(n-1)^2/((n-1)^2+(n-2)^2)\ldots..2(3)^2/(3^2+2^2)*2(2)^2/(2^2+1^2)]\ \sigma_I$ (11)

The reflected stress σ_R is determined using eq. 9

$\sigma_{R(n-1)}= [\ (A_{n-1}-A_n)/(\ A_{n-1}+A_n)]\ \sigma_I = [\ (n-1)^2 - n^2/((n-1)^2+n^2)]$ (12)

This reflected stress is added to other arriving stresses resulting from the multi- reflections at the interface.

Special cases:

i) If the rod is made of the same material but encounters only change in cross sectional area, Fig.1 (a), the incident and reflected waves will have the same or opposite signs, compression or tension, according to the increase or decrease in size of the cross sectional area: and at the same time the intensity of the transmitted stress, σ_R, falls below or exceeds the intensity of the incident stress, σ_I. This is of course only true inside the material but not at its end surfaces. ii). If the rod is of uniform cross sectional area but made of two materials have different acoustic impedances ,ρC,, Fig.1 (b), then the intensity of the transmitted stress value exceeds or falls below the incident stress level according to whether ρ2C2 is higher or lower than ρ1C1 respectively. Furthermore the incident and reflected waves will have the same sign in this case, whereas the reflected wave will have opposite sign to the incident wave if ρ2C2 is lower than ρ1C1. It can also be noted that the transmitted wave has the same sign as the incident wave.

iii) If A2/A1 is about zero i.e. the end of the rod is free end then $\sigma_R = -\sigma_I$.

iv) If A2/A1 is &i.e the end of the rod is effectively fixed then $\sigma_R = \sigma_I$ and $\sigma_T= 0$. It can be concluded from equations(4) and (5) that if a small shaft is placed at the end of a shaft of larger cross sectional area, it will act as a momentum trap to the stress wave or pulse. This was utilized in treatment of scabbing caused at the end of a mild steel plate partially cut by a linear explosive shaped charge as will be discussed later in the paper.

2.2 Applications of elastic stress waves

Elastic stress waves were applied successfully in the following:

1) Determining the mechanical behaviour of materials under dynamic loading

The Hokinson and the split Hopkinson pressure bars which utilize the concepts of elastic stress waves transmission and reflection were successfully used in determining the mechanical behaviour under compressive, tensile, and torsional. The description of these methods is beyond the scope of the paper, and can be found in Refs.,[ ].

2) Producing multi-layered and laminated sheets
Multi-layered and laminated sheets (either reinforced with carbon or glass fibers or without reinforcement) by explosive welding.

3) Production of laminated or duplex cylinders
Duplex and laminated cylinders of identical or different materials were successfully produced using either explosive or implosive welding by the aid of a wave shaper to generate a plane wave along the length of the cylinders.

4) Production of solid cylinders from thin cylindrical rods. This a recent application of utilizing stress waves in producing a solid cylinder from thin cylindrical rods made of four different materials namely: mild steel, stainless steel, copper and brass in the middle carried out by the author using the implosive welding process. The produced cylinders were successfully extruded and drawn without any separation of the rods. Other blanking tests were carried out on specimens of 3 mm thickness and no sign of separation or fracture on any of the welding interfaces. It is very interesting to mention that the above explosively welded parts are produced by the same mechanism of jet formation. The most interesting feature is that the mechanism of jet formation which was used in the welding process is the same one which will be used in perforation and cutting by lined cavity shaped charge as will be discussed in another paper in this conference, [18 (a) and (b)].

5) Separation of welded multi-layered sheets and laminated cylinders. These products were produced by the transmitted compressive stress waves produced from the explosive charge and are separated by either the reflected tensile waves or the interaction of the transmitted and reflected waves. Zaid, [18 (a) and (b)] analyzed the transmission, reflection and interaction of stress waves in explosively welded multi-layered sheets and discussed the separation between the different layers and showed how it can be avoided. The separation is caused by the reflection of the compressive waves as tensile waves from the surface of the inside cylinder.

2.3 Fractures caused by stress waves

Three types of fracture are caused by longitudinal stress waves:

a) Due to incident and transmitted stress waves

b) Due to reflected stress waves, and the interaction of the transmitted and reflected stress waves.

The criterion used for the fracture of materials in this section is: material fractures when the stress level at any section in the material reaches the dynamic fracture stress of this material, it will fracture depending on the type of stress e.g. tension, compression, or shear. Table 2 gives the dynamic fracture stresses of some materials.

Table 2: Dynamic fracture stress of some materials

Materials	Dynamic fracture stress N/m^2
Copper	$2.282*10^9$
Brass	$2.13*10^9$
4130 steel	$3.03 *10^9$
1020 steel	$1.10 *10^9$

In this paper, only fractures caused by both longitudinal waves are discussed.

2.4 Different fractures caused by stress waves

Three types of fracture are caused by longitudinal stress waves:

Due to incident stress waves. If the stress intensity of the incident pulse is higher than the corresponding dynamic fracture stress of the material which it impinges on, the material will fracture if the material is perfectly elastic, homogeneous, isotropic and there is no attenuation, change in shape, or variation in the velocity of propagation. If the intensity of the incident stress is lower than the dynamic fracture stress of the material and it meets a stress discontinuity, (either due to change in cross sectional area or acoustic impedance such that it will cause amplification of its value it will also cause fracture. Fig.3 shows amplification of a compressive stress impinging on the large end of a conical rod.

The transmitted stress, $\sigma_{T,}$ at any section determined using equation 10. which enables the transmitted stress at any section along the rod length to be determined. The results are plotted in Fig.3 for different values of n. it can be seen from Fig.3 that the incident compressive stress gets amplified as it proceeds towards the apex. Furthermore, it can be seen from the figure that the approximation converges for values of n larger than 96, as little difference exists between curves 5 and 6, for 96 and 192 steps, therefore 96 steps is considered adequate. Depending on the magnitude of the incident compressive stress, if the amplified transmitted stress at any section along the rod just exceeds the dynamic fracture compressive strength of the rod material it will cause the rod fracture at this section although the incident stress, $\sigma_{I,}$ may be less than the elastic limit stress of the rod. Following the same approximation Zaid has also given the variation of the compressive pulse at the tip of a triangular projectile, [22(a) and (b)].

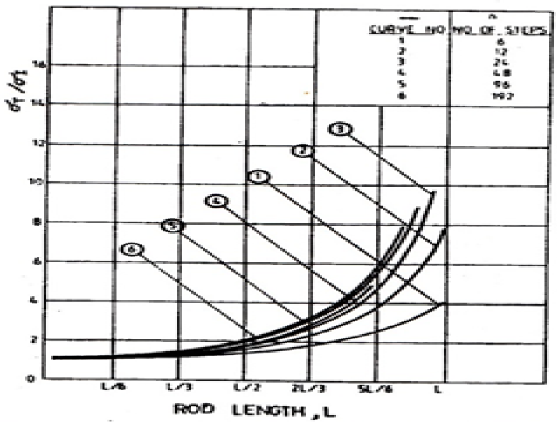


Fig.3: Amplification of the stress

If an incident triangular compressive stress pulse is transmitted along anisotropic conical rod, Fig.4, without meeting a stress discontinuity, when it reaches the free end it will be reflected due to reflected stress wave.

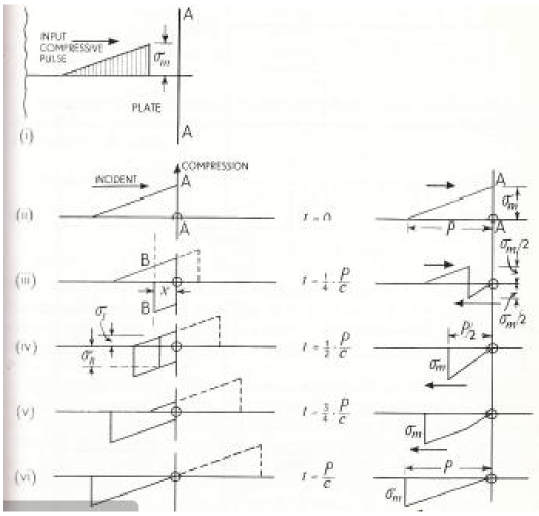


Fig. 4: Interaction of the transmitted compressive wave and the reflected tensile wave, [9].

2.4.1 Scabbing and multiple scabbing

Whilst long recognized as a phenomenon in Hopkinson reported work on the use of the pressure bar further to the measurement of the compressive pressure wave resulting from the detonation of the guncotton, the destructive effects of the latter when placed in contact with a thick steel plate were also considered. The fracture of the plate was shown to be brittle, or "short" with little plastic flow. Although the fractures were not associated with reflected stress waves at that time and were described as "Hopkinson fractures". Rinehart was the first to report a quantitative investigation into the fracturing of metals due to reflected waves. The following assumptions were made:

(i) The compressive wave is plane and approaches the free surface normally and suffering reflection without change in intensity.

(ii) The material is perfectly elastic, homogenous, and isotropic and there is no attenuation, change in shape, or variation in the propagation velocity. Regardless of the stress level.

(iii) The fracture forming the scab r the spall occurs instantaneously.

A further fracture reported by Rinehart, is the multi scabbing. It occurs if the incident compressive wave is of sufficient intensity, then after the first scab, the remaining part of the compressive wave will also suffer at the newly created free surfaces and further scabs will be produced. This is made clear by reference to the multi scabs reported in Refs. [9, 11, 12]. Ever since work on scabbing and multiple scabbing continued. In general, the experimental results of Obrien and Davis substantiate the mechanism advanced for scabbing and multi scabbing, although they reported that their observations of multi-scabbing were in qualitative agreement with those of Rinehart but the position of the second scab was closer to the first than would be predicted from the profile of the pressure wave.

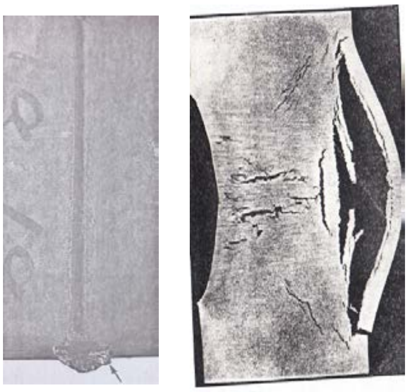

a *b*

Fig.5: Scabbing and multiple scabbing of a mild steel plate, (a) at the end of a cutting jet from aliened cavity angle shaped charge, (b) From a contact high explosive charge

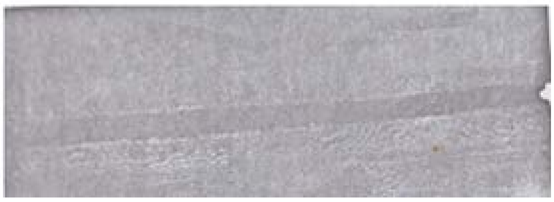


Fig.6: The mild steel plate in (a) after treating the scab by using a momentum trap

2.4.2 Momentum traps

Fig.7 shows a uniform cylindrical bar (1), of length L1 and cross-sectional area A_1, to the end of which is lightly attached a bar (2) of length L2 and cross sectional area A_2, with $A_1>A_2$; also L1 >L2. The mating surfaces of the two bars are carefully scraped fit and a smear of greaese is applied to ensure close contact.

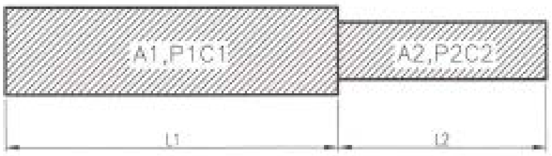


Fig.7: The general case of a plane of stress discontinuity

If at the end of bar (1) is applied a constant intensity compressive stress of magnitude σ, the incident compressive stress is transmitted by the attached bar as a compressive wave, and later reflected from its free end as a tensile wave. It then reaches the interface, the common plane to bar (1) and bar (2). The stress at any position is then found by the summing the incident and reflected waves. As the interface is unable to withstand tension, hence immediately contact ceases; bar (2) moves off processing a certain kinetic energy and having trapped some of the momentum in the incident pulse. It is the same concept which was used by Hopkinson to determine the general form of the incident compressive pulse from an explosive or from an impact blow using pieces of different thicknesses, and measuring the momentum entrapped within each piece, [2]. The same method was used by the author to avoid scabbing of the plate in Fig.6

3 Conclusions

In this paper, the following points are given:

i) The old and recent literatures are reviewed which includes: the history of the phenomena and its Theoretical aspects.

ii) The useful applications of stress waves are given and discussed.

iii) The damages caused by their transmission, reflection and interaction (scabbing and multiple scabbing) are given and discussed. Finally, the method for their avoidance using the momentum trap is also given and discussed.

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