STRESS WAVE ATTENUATION DURING BALLISTIC IMPACT ON A CERAMIC TARGET

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Abstract

Stress wave attenuation studies are presented for longitudinal radial waves propagating within a ceramic plate made of hexagonal tiles bonded with an adhesive. Whenever a stress wave reaches an interface between the ceramic tile and the adhesive layer, reflection and transmission of the incident stress wave takes place. This is because of the impedance mismatch at the interface. Reflection and transmission of the incident stress wave would lead to attenuation of stress waves. An algorithm is presented for tracking the stress waves. The total intensity of the stress waves in a region is obtained. It is generally observed that the stress wave attenuation can be significant as it propagates within the ceramic plate made of hexagonal tiles. Study is carried out to investigate the effect of different parameters on stress wave attenuation.

1 Introduction

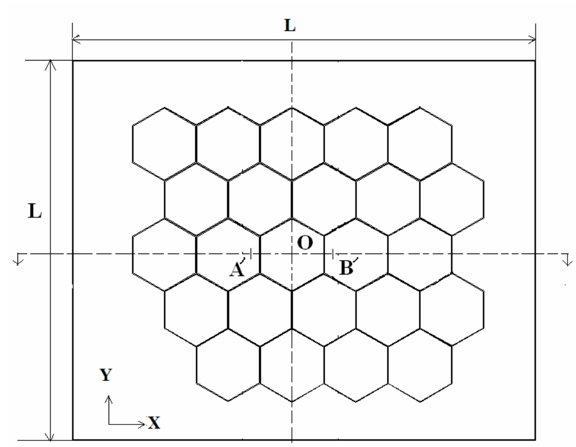
When there is a transverse impact of a projectile on to a target, longitudinal and transverse stress waves are generated in the target along the thickness and radial directions. The waves generated undergo reflection and transmission when they reach any interface across which impedance is different. At the interface, transverse and longitudinal waves are formed. The stress wave attenuation would take place as the wave propagates away from the point of impact because of impedance mismatch at different interfaces.

The objective of present study is to investigate longitudinal stress wave attenuation along radial direction in ceramic plates made of hexagonal tiles. It is based on reflection and transmission of stress waves. Further, parametric studies are carried out to find the normalized stress intensities in ceramic plate along radial direction. Studies are carried out using one-dimensional wave propagation in solids for thin ceramic plates.

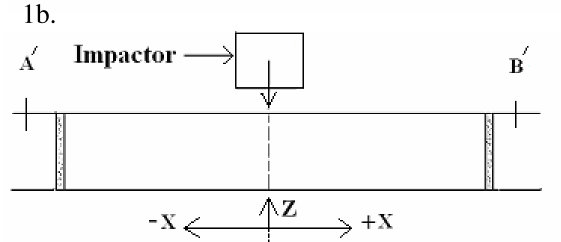
2 A Typical Ceramic Plate Made of Tiles

The ceramic plate is made of hexagonal tiles bounded by adhesive (Fig. 1a). The dimensions of ceramic plate are: L x L where L is 300 mm. In the present study the plate undergoes a ballistic impact at point O, center of a typical tile, by a projectile of radius, r as 5 mm (Fig. 1b). The hexagonal ceramic tile has inner diameter, a as 50 mm (Fig. 1c), and width, b of adhesive around the hexagonal tile is 1 mm (Fig. 1c). A schematic diagram of reflected and transmitted waves when a one-dimensional longitudinal wave passes through an interface between material A and material B is shown in Fig. 1d. Both ceramic and adhesive are considered to be isotropic.

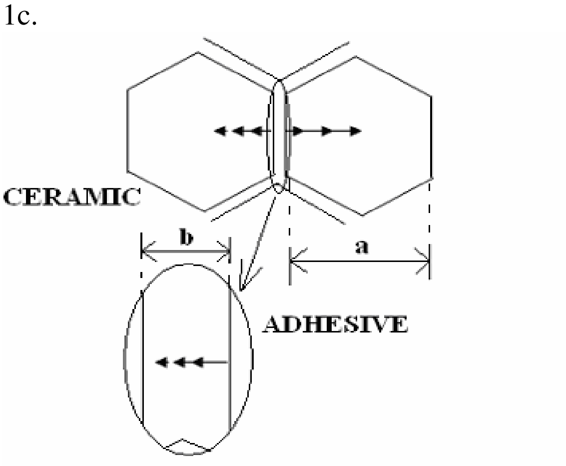
1a.



1b.



1c.



1d.

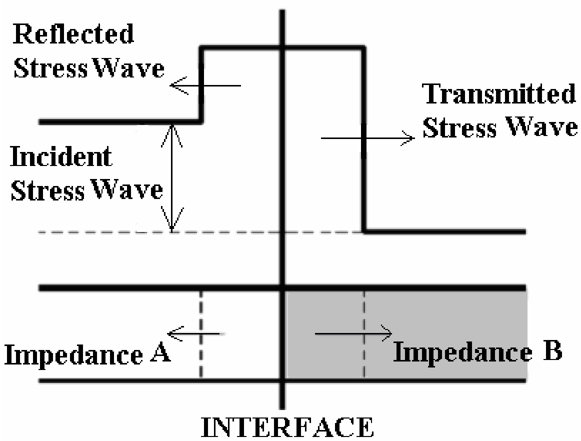


Fig. 1. Transverse impact of a projectile on a ceramic target, (a) geometry, (b) projectile hitting the target, (c) schematic representation of reflected and transmitted stress waves in ceramic tile and adhesive, (d) schematic representation of incident, reflected and transmitted waves at interface.

3 Theory

Reflected and transmitted components of the stress wave are calculated as [1]:

$$\sigma_T = \frac{2\rho_B C_B \sigma_I}{\rho_B C_B + \rho_A C_A} \qquad (1)$$

$$\sigma_R = \frac{(\rho_B C_B - \rho_A C_A)\sigma_I}{\rho_B C_B + \rho_A C_A} \qquad (2)$$

At free surface: $\sigma_T = 0,\ \sigma_R = -\sigma_I$ (3)

At rigid boundary: $\sigma_T = 2\sigma_I,\ \sigma_R = \sigma_I$ (4)

Here, σ_I, σ_R and σ_T represent intensities of the incident, reflected and transmitted waves, respectively. $C = \sqrt{(E/\rho)}$ is stress wave velocity, E is the elastic modulus and ρ is the density of the medium. Subscripts A and B refer to materials A and B, respectively.

The ceramic target gets perforated and a hole is created around the point of impact. The formation of hole would take place as the projectile proceeds in thickness direction.

4 Wave Tracking Algorithm

The studies are carried out for the incident stress wave intensity of 1 unit. The hole boundary is considered to be a free surface, with transmitted and reflected stress intensities as per Eq. (3).

As the initial incident wave encounters the interface, transmitted and reflected waves are formed. This process continues leading to many waves of different intensities. The algorithm developed allows all waves to be tracked at a predefined time interval. In the present study the time interval considered is 1 nanosecond.

The waves generated are considered to be dead if their intensity becomes lower than a predefined threshold. In the present study, the threshold is considered as 1 % of the intensity of the incident wave due to impact.

If the origin, geometry, and material properties are such that any wave reaches the boundary of ceramic plate then depending upon the type of boundary, whether rigid or free, the resultant waves are governed by Eq. (3) and Eq. (4). The plate boundary is considered as free surface in the present study.

In the base study, properties of ceramic are: E_{C0} = 372 GPa and ρ_{C0} = 3420 kg/m^3, and for adhesive are: E_{A0} = 3.5 GPa and ρ_{A0} = 1200 kg/m^3. Dimensions for the base study are: L = 300 mm, r = 5 mm, a = 50 mm and b = 1 mm. The simulation time considered in base study is 15 μs, which is essentially the impact duration. Apart from this, simulation is also done till the time all the waves die down, which is referred to as stable state. Time for stabilization of stress intensity is generally found to be around T = 160 μs. Plots for the base study and the various parametric studies are presented in next section. All these plots are generated using the algorithm presented above. The reflected and transmitted intensities for the base material are shown in Table 1.

Table 1. Transformation of stresses through interfaces using Eqs. (1) and (2)

Interface	Transmitted Wave Intensity (σ_T)	Reflected Wave Intensity (σ_R)
Ceramic to adhesive	$0.11\ \sigma_I$	$-0.89\ \sigma_I$
Adhesive to ceramic	$1.89\ \sigma_I$	$0.89\ \sigma_I$

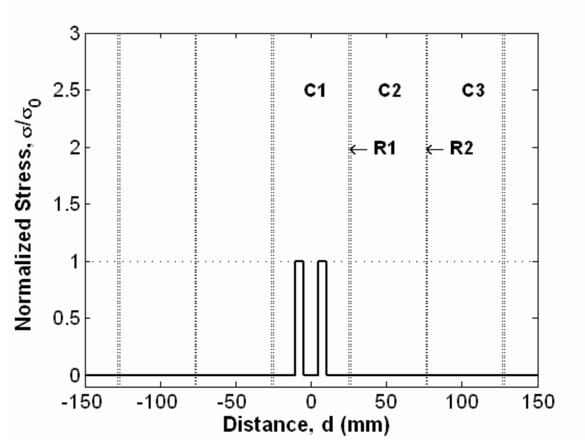
5 Results and Discussion

5.1 Base study

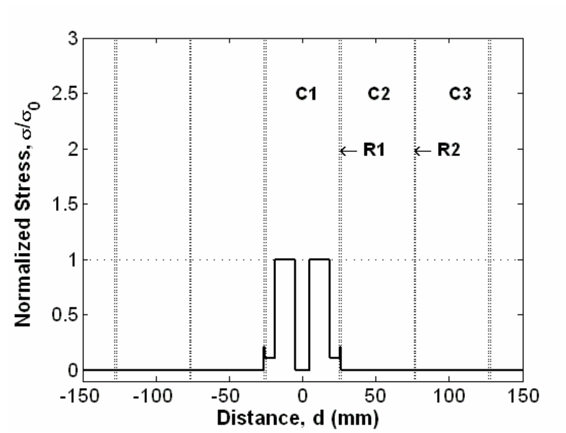
Plots of normalized stress as a function of distance from the point of impact are presented in Fig. 2 for different simulation times. The distance up to which the wave has traveled at 0.5 μs is shown in Fig. 2a. It is within the first ceramic tile. At about 2.4 μs, the incident wave reaches the first interface between ceramic tile and adhesive. The transmitted and reflected stress waves generated are governed by Eqs. (1) and (2). This is shown in Fig. 2b which is for $T = 2.5$ μs.

Figure 2c is for T = 15 μs. Independent analytical studies have shown that T = 15 μs is the impact duration. In this time, the stress waves have reached up to a distance of 127 mm from the point of impact and the normalized stress intensity is less than 0.01. Damage has spread to the first tile on which the impact took place and partly into the adjacent tiles. Independent experimental studies have shown similar observations. Figure 2d shows the stress distribution for T = 160 μs, when all the waves have died down, and this is the stabilized stress distribution in ceramic due to the impact event. It can be observed that at T = 15 μs, normalized stress increases within the first tile and then it decreases gradually in adjacent tiles. On the other hand, at T = 160 μs, normalized stress remains constant within each tile.

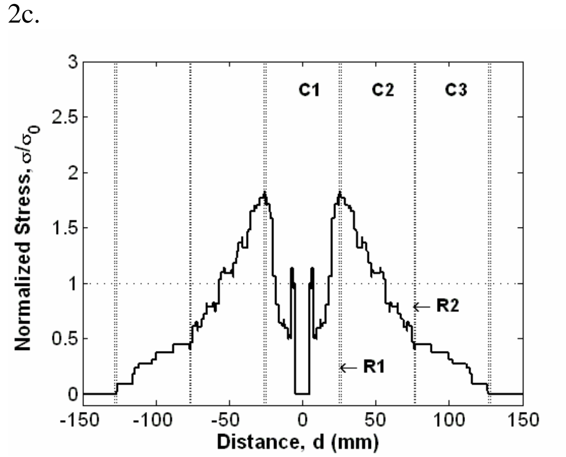
2a.



2b.



2c.



2d.

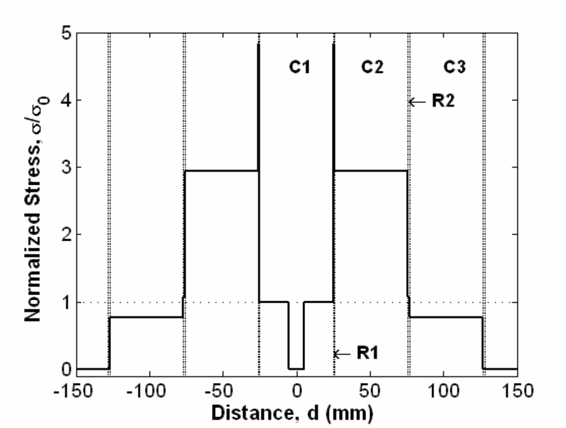


Fig. 2. Distribution of normalized stress wave intensity in the ceramic plate for different simulation times, T = (a) 0.5 µs, (b) 2.5 µs, (c) 15 µs, (d) 160 µs.

Notations C1, C2 etc. in the figures correspond to 1st ceramic tile, 2nd ceramic tile etc. whereas R1 corresponds to adhesive bond between 1st and 2nd ceramic tile, R2 corresponds to adhesive bond between 2nd and 3rd ceramic tile and so on.

5.2 Parametric studies

5.2.1 Effect of plate dimension

It may be noted that, stress waves are reaching only up to a distance of 127 mm for the base study. Thus stress wave attenuation behavior would remain the same for the plates having plate dimension more than the plate dimension of base study. Parametric studies are carried out by changing the plate dimension to L = 150 mm, 200 mm and 250 mm for T = 15 µs (Fig. 3) and for T = 160 µs (Fig. 4). For L < 254 mm, reflections and transmissions also take place from the free boundary of plate. Table 2 shows values of normalized stress intensity at different distances from the point of impact for various plate dimensions, both for T = 15 µs, and T = 160 µs. For L = 150 mm, the effect of plate dimension is significant.

Asterisk (*) indicates that for the given case, the stable time was found to be 260 µs and not 160 µs as for other cases. This is expected because for L = 150 mm, the second interface is replaced by free surface which is not causing any attenuation.

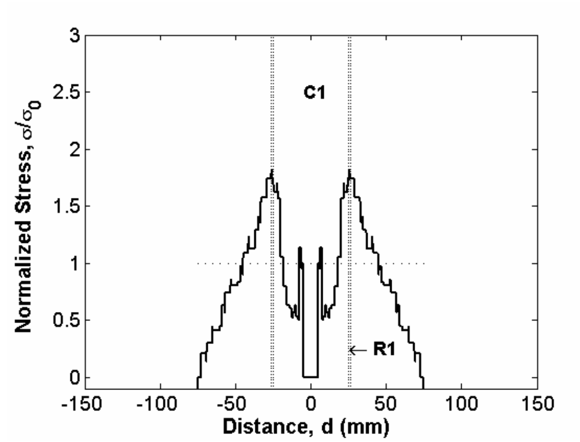
It is observed that the peak normalized stress wave intensity occurs in the adhesive R1, for all the cases examined.

Table 2. Normalized stress intensities for different plate dimension, L

L (mm)	Distance from impact, d (mm)					
	25-	25+	50	75	100	125
			T = 15 µs			
150	1.68	1.748	0.80	0	-	-
200	1.70	1.769	1.09	0.46	0	-
250	1.70	1.769	1.09	0.46	0.27	0
300	1.70	1.769	1.09	0.46	0.31	0.09
			T = 160 µs			
150*	1	3.77	0	0	-	-
200	1	4.83	2.94	2.94	0	-
250	1	4.83	2.94	2.94	0	0
300	1	4.83	2.94	2.94	0.76	0.76

*T = 260 µs

3a.



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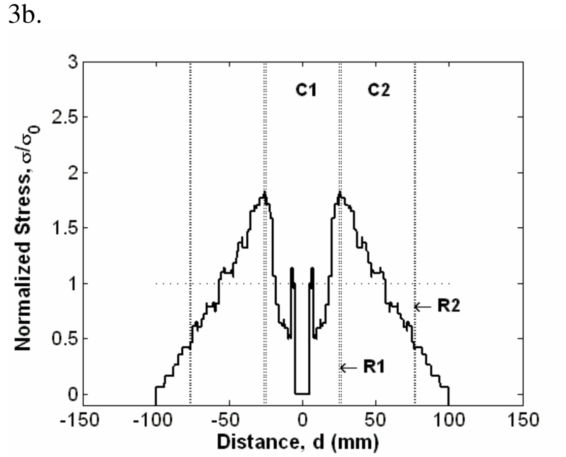
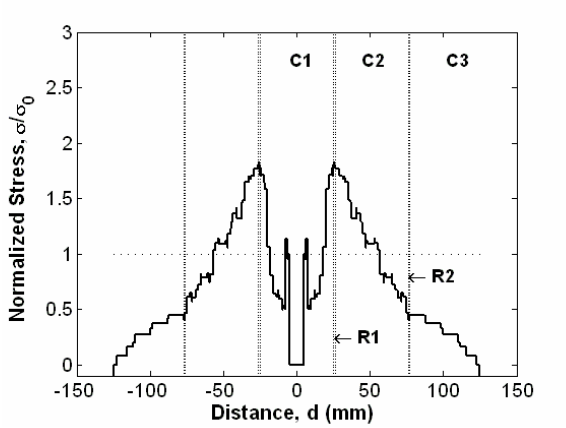


3c.



3d.

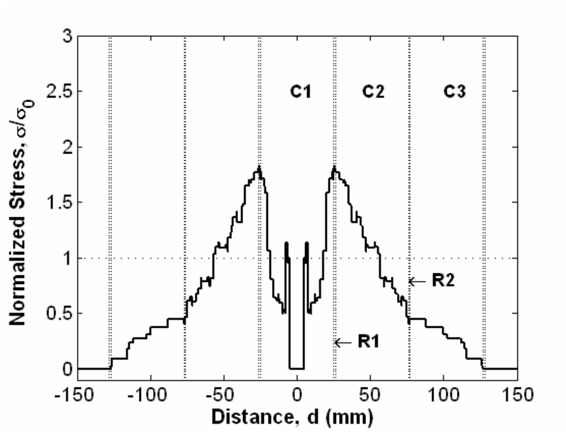
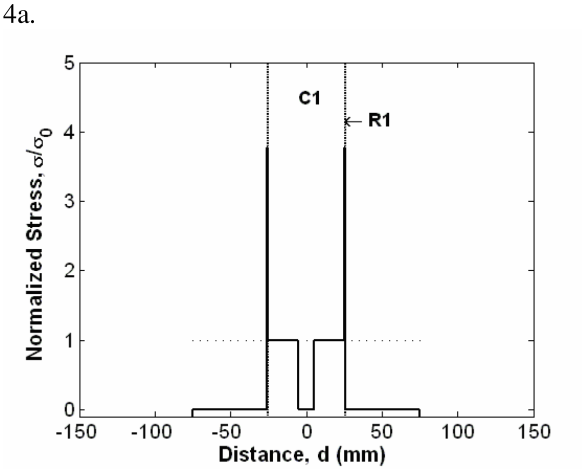
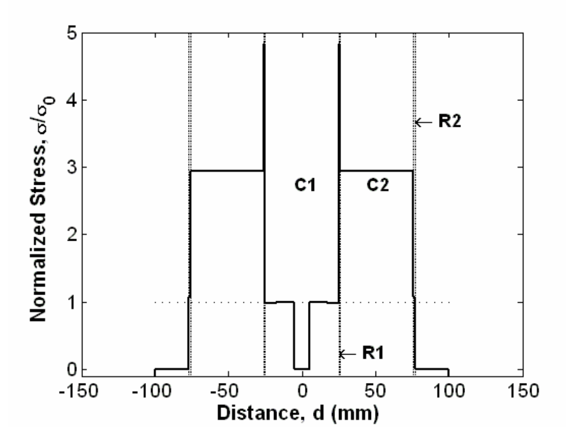


Fig. 3. Distribution of normalized stress wave intensity in the ceramic plate at T = 15 μs for different plate dimensions, L = (a) 150 mm, (b) 200 mm, (c) 250 mm, (d) 300 mm (base study).

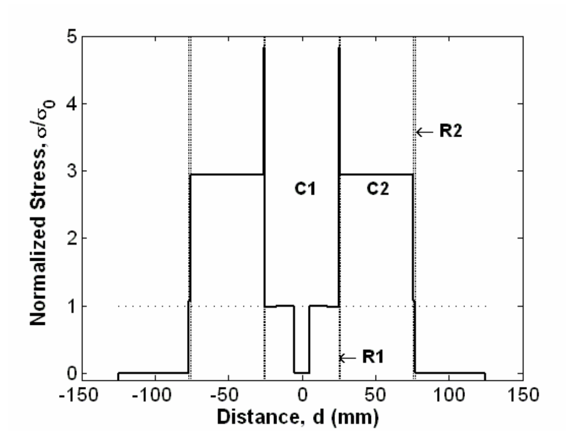
4a.



4b.



4c.



4d.

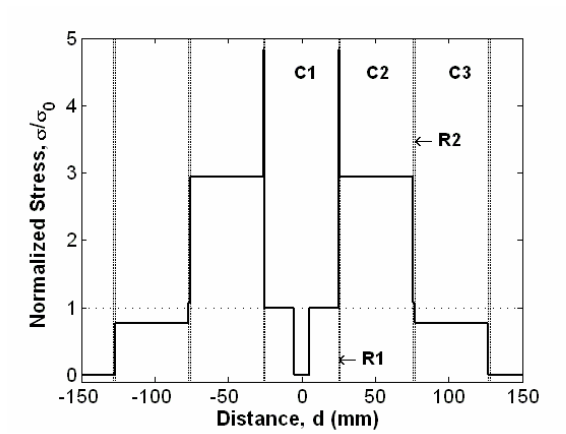
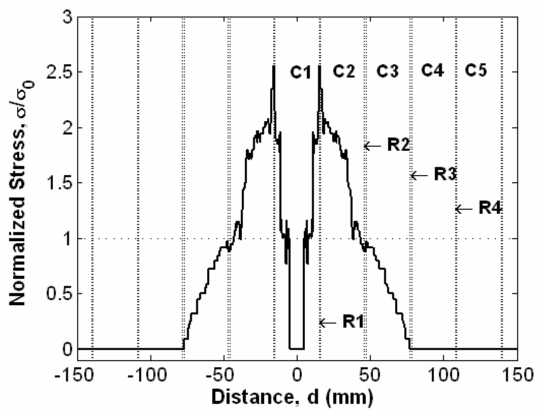


Fig. 4. Distribution of normalized stress wave intensity in the ceramic plate at T = 160 μs for different plate dimensions, L = (a) 150* mm, (b) 200 mm, (c) 250 mm, (d) 300 mm (base study).

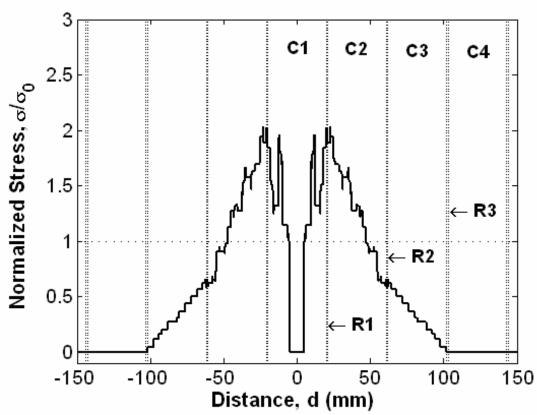
5.2.2 Effect of ceramic tile dimension

Parametric studies are carried out with size of hexagonal ceramic tile, *a* = 30 mm, 40 mm, 50 mm and 60 mm for *T* = 15 μs (Fig. 5). It is observed that as tile dimension increases peak stress intensity decreases. Peak normalized stress wave intensity occurs in the adhesive R1, for all the cases examined. However, at larger distances from the point of impact, normalized stress intensity increases. Also the spread of waves increases.

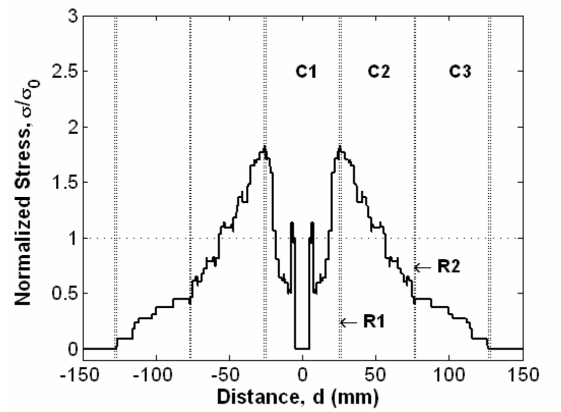
5a.



5b.



5c.



5d.

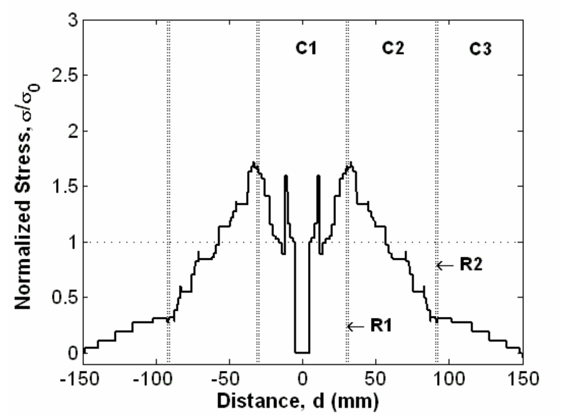
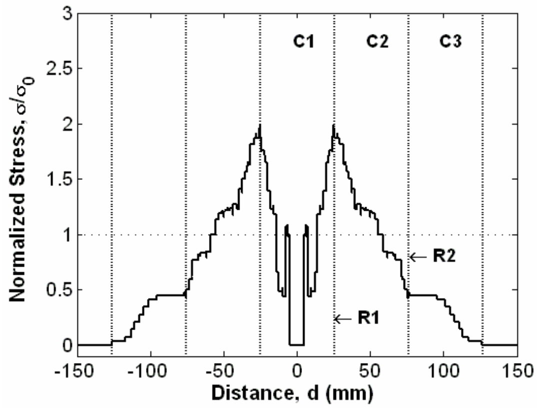


Fig. 5. Distribution of normalized stress wave intensity in the ceramic plate at T = 15 μs for different ceramic tile dimension, a = (a) 30 mm, (b) 40 mm, (c) 50 mm (base study), (d) 60 mm.

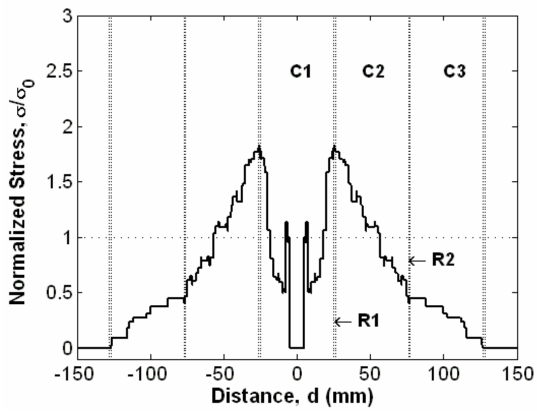
5.2.3 Effect of adhesive dimension

Parametric studies are carried out with size of adhesive, *b* = 0.5 mm, 1 mm, 2 mm and 5 mm (Fig. 6). It is observed that as adhesive dimension increases normalized stress as well as spread of waves decrease.

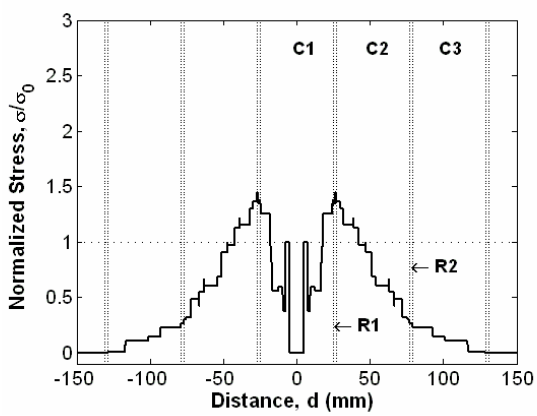
6a.



6b.



6c.



6d.

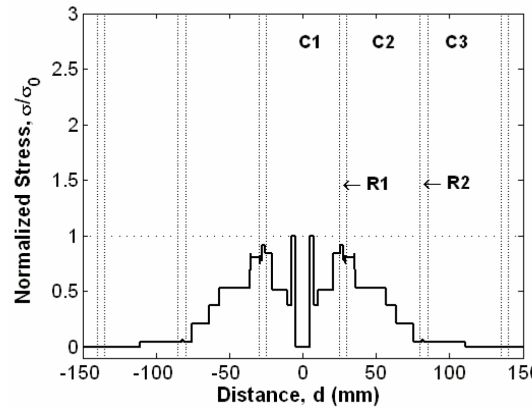


Fig. 6. Distribution of normalized stress wave intensity in the ceramic plate at T = 15 μs for different adhesive dimension, b = (a) 0.5 mm, (b) 1 mm (base study), (c) 2 mm, (d) 5 mm.

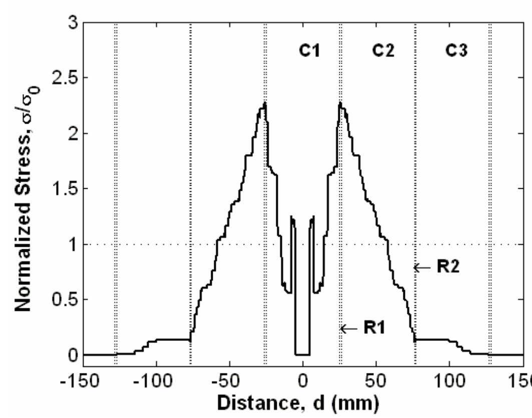
5.2.4 Effect of projectile dimension

Parametric studies are done by varying the impactor radius to r = 2.5 mm, 5 mm, 7.5 mm and 10 mm. But no significant effect is observed, hence results are not presented.

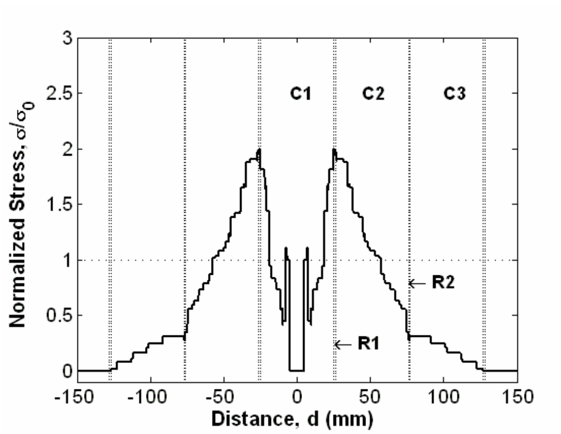
5.2.5 Effect of density of adhesive

In another parametric study, density of adhesive is varied as $\rho_A = 0.6\rho_{A0}$, $0.8\rho_{A0}$, $1.0\rho_{A0}$ and $1.2\rho_{A0}$. Here ρ_{A0} is the adhesive density of base material. It can be observed from Fig. 7 that as ρ_A increases spread of waves increases, whereas normalized stress decreases. This happens because for lower ρ_A impedance mismatch is more hence there is more attenuation, so spread decreases.

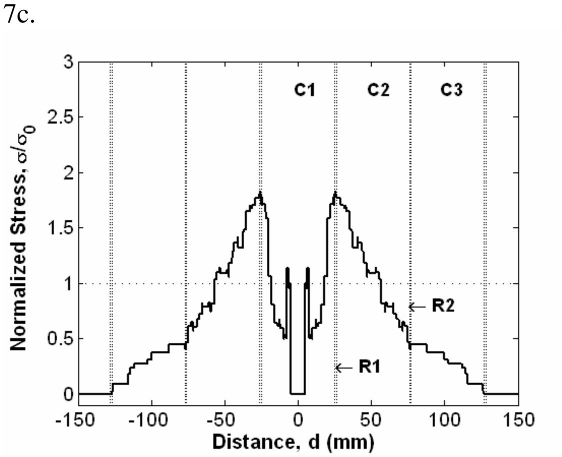
7a.



7b.



7c.



7d.

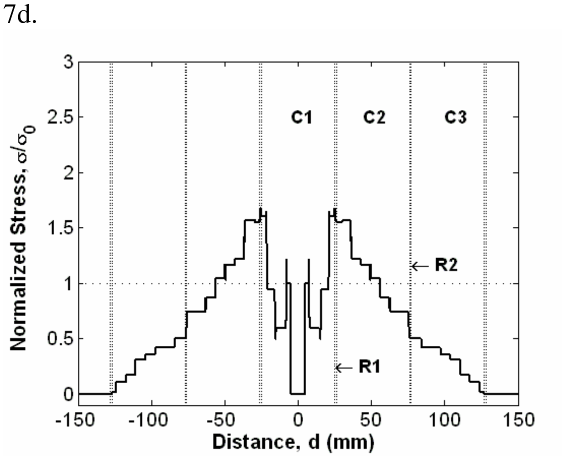
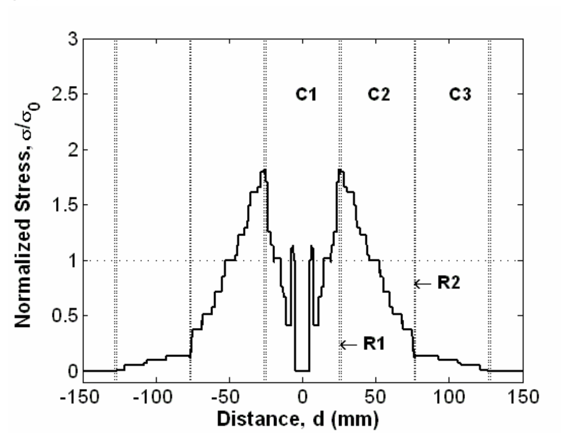


Fig. 7. Distribution of normalized stress wave intensity in the ceramic plate at T = 15 μs for different adhesive density, ρ_A = (a) $0.6\rho_{A0}$, (b) $0.8\rho_{A0}$, (c) $1.0\rho_{A0}$ (base study), (d) $1.2\rho_{A0}$.

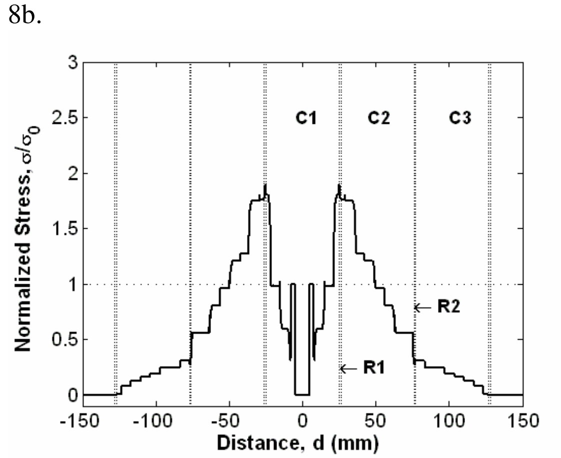
5.2.6 Effect of elastic modulus of adhesive

In this parametric study, the elastic modulus of adhesive is varied to $E_A = 0.6E_{A0}$, $0.8E_{A0}$, $1.0E_{A0}$ and $1.2E_{A0}$. Here E_{A0} is the elastic modulus of base material. It can be observed from Fig. 8 that as E_A increases spread of waves increases, whereas normalized stress increases slightly at distances away from the point of impact. This happens because for lower E_A, impedance mismatch is more hence there is more attenuation, so spread decreases.

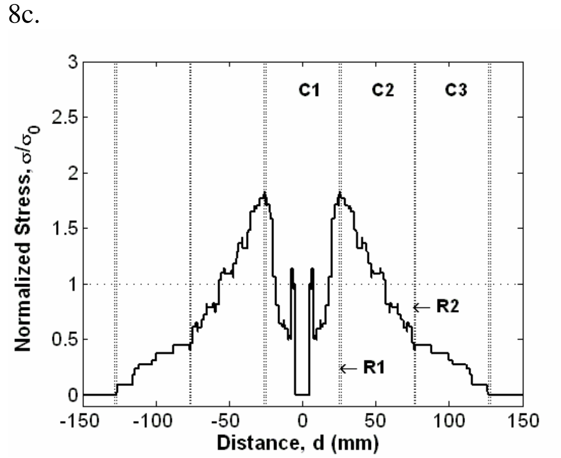
8a.



8b.



8c.



8d.

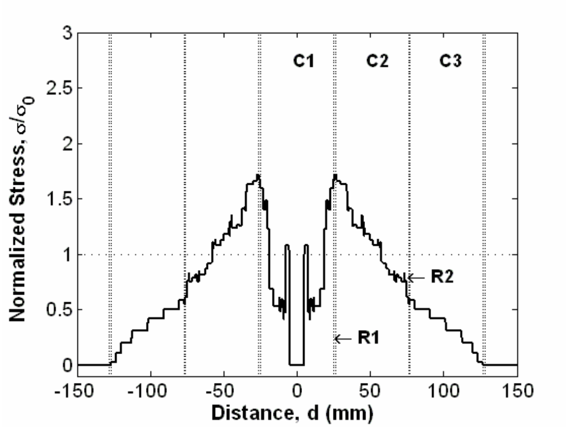


Fig. 8. Distribution of normalized stress wave intensity in the ceramic plate at T = 15 μs for different elastic modulus of adhesive, E_A = (a) $0.6E_{A0}$, (b) $0.8E_{A0}$, (c) $1.0E_{A0}$ (base study), (d) $1.2E_{A0}$.

5.3 Micro attenuation

In a separate study, attenuation of wave is also accounted in the ceramic region considering the difference in elastic modulus and density of the grain and the grain boundary.

Stress wave attenuation at grain and grain boundary level is referred to as micro attenuation. Micro attenuation is defined in terms of attenuation coefficient, α_C. Attenuation coefficient is a material property. It is observed that attenuation is more when micro attenuation is also considered along with the attenuation because of the interface between the ceramic tile and adhesive.

6 Concluding Remarks

A method is presented to predict stress wave attenuation in a ceramic plate made of hexagonal tiles when impacted by a rigid projectile. This is because of impedance mismatch at ceramic tile - adhesive interface. Studies are carried out to investigate the effect of various parameters such as effect of plate dimension, ceramic tile dimension, adhesive dimension, projectile dimension, density of adhesive and elastic modulus of adhesive on attenuation behavior.

References

[1] Meyers M. A. "*Dynamic behavior of materials*". John Wiley, New York, 1994, pp. 45-50.