TIME SCALING FOR DYNAMIC SPALL FRACTURE

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ABSTRACT

Glass material with its various application is very sensitive to impact loading. Under impact condition where stress waves and their interaction are dominant, failure may be initiated simultaneously at some sites. The strength of material varies rapidly with loading rate and fracture time. This study, based on previous works on cumulative damage models, concerne a float glass and lead crystal subjected to impact at different loading rate. In order to evaluate the damage development and the fragmentation, we propose a damage model characterized by the damage volume affected by impact.

1. INTRODUCTION

It is well known that in a component, both phenomena fracture strength and peak stress are strain rate sensitive. This also true for glass specimen. In addition static fracture leads to simple fracture initiates from the biggest defect, dynamic fracture occurs by multifragmentation owe to defect multi-activation. This specific phenomenon of dynamic fracture increase also scatter in experimental results. For dynamic Spall fracture, damage process volume is also sensitive to loading rate and more precisely to fracture time. Spalling is generally described by empirical relationship between fracture stress and critical (fracture) time. been realized. Tuler and Butcher [1] proposed a spall fracture criterion based on cumulative damage concept as:

$$\int_0^{t_c} (\sigma - \sigma_0)^{\lambda}\, dt = C \tag{1}$$

where λ and *C* are material constants, σ_0 is the threshold stress and t_c is the fracture time. Klepaczko [2] suggested another relationship where the power exponent depends on activation energy and temperature ΔG_0. The proposed cumulative fracture criterion is presented in an integral form as follow:

$$\int_0^{t_c} \left(\frac{\sigma(t)}{\sigma}\right)^{\alpha(T)} dt = t_{co};\;\; t_c \le t_{co},\;\; \sigma \ge \sigma_0 \qquad \alpha(T) = \frac{\Delta G_0}{kT} \tag{2}$$

where σ_0, t_{co}, and $\alpha(T)$ are three material constants for constant temperature T. t_{co} is the longest critical time when $\alpha(t_{co}) = \alpha_0$. The exponent $\alpha(T)$ depends on the absolute temperature T and is related to the activation energy ΔG_0, with k the Boltzmann's constant.

In this paper, relationship between fracture stress and critical time has been established for two materials, float glass and lead crystal. A new model based on damage accumulation to describe relationship between these two parameters has been proposed. Critical time is considered as the necessary time to build in the fracture volume process where the damage cumulation reachs a critical level. This model gives a physical meaning to the constants of the Tuler and Butcher and Klepacko models.

2. MATERIALS, EXPERIMENTAL DEVICE AND RESULTS

2.1 SPLIT HOPKINSON PRESSURE BARS DEVICE

Test were performed on a Split Pressure Hopkinson Bars devices which allows dynamic loading at high strain rate (10^2 and 10^{-4} /s) and on Drop Ball test (DBT) which consists of dropping a steel ball of 55g. from variable height. The ball is guided in order to focuse the impact in the middle of the sample (see Fig.1). Strain amplitude measured with strain gages was recorded on a digital oscilloscope 440).

2.2 MATERIAL

FLOAT GLASS

The material considered is a float glass. Sample dimensions is $100x100x5mm^3$. The mean chemical composition is 70.6% SiO, 9.8% CaO, 13.8% Na_2, 4% MgO and others impurities. The main properties of this glass are presented in table1.

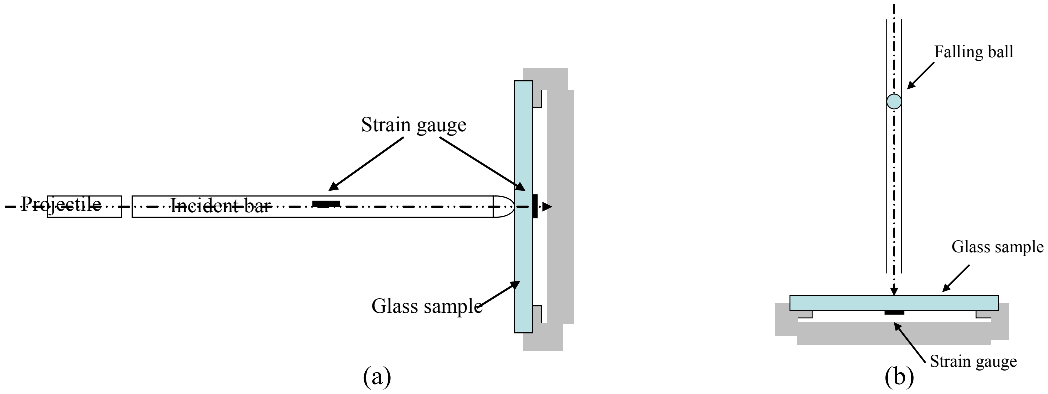


Fig. 1 Schematic illustration of Split Hopkinson Pressure Bars (a) and Drop Ball test (b)

Mechanical properties	Poisson ratio	Young's modulus	Density
Values	0.23	70 GPa	$2508kg/m^3$

Table1 : Mechanical properties of float glass

Fig. 2 presents experimental results of critical stress versus critical (fracture) time. Critical event is determined by strain gauge signal during which exhibits a sudden drop. Experimental results indicate clearly a power decreasing function is a function of critical stress σ_c with fracture time t_c. On the same picture, experimental data were fitted with Klepaczko's and Tuler and Bucher's models with the most appropriate values of the two empirical constant values. From Fig. 5 and Eq.1, typical values of the constants for glass at the room temperature were obtained: σ_0 = 40MPa, and α = 1.25.

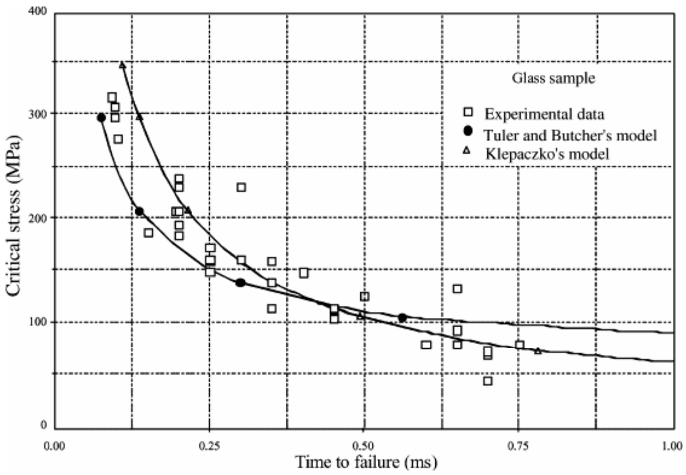


Fig. 2. Comparison of critical stress-time to failure evolution between experimental data and Tuler's and Klepaczko's models (2001, S. Bouzid [3]).

Dynamic fracture mechanism is modified with the loading rate and may be with the used devices, i.e., drop ball test (DBT) and Split Pressure Hopkinson bars. (Fig.3). Fracture paths determined on float glass are presented on the following pictures. Loading rate is different in each case from one order of magnitude

LEAD CRYSTAL

Similar results have been obtained on lead crystal using another type of specimen. The used specimen has the geometry of the Brezilian disk and includes a small hole into the center of specimen. This stress concentrator localized the indirect tensile strength produce by dynamic compression wave. This particular specimen is called Modified Brazilian Disk (MBD). The chemical compositions of this lead crystal are : 58% SiO, 28.85% PbO, 5.43%

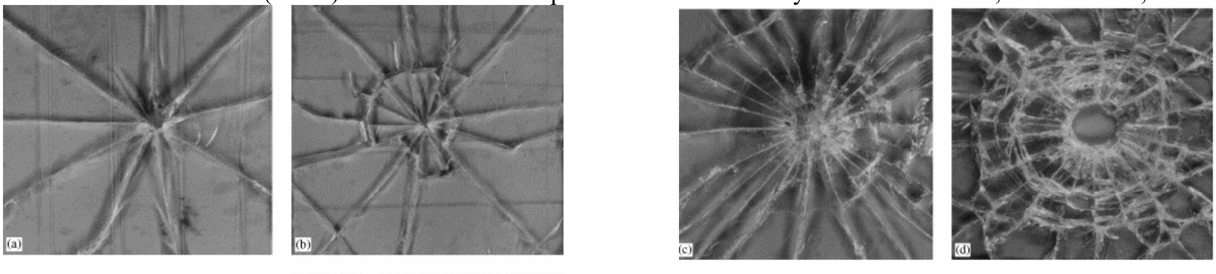


Fig. 3 Pictures of fracture paths obtained from two different loading rates (a and b) – test performed by drop ball test (low loading rate),-test performed by Hopkinson bars (high loading rate)

Na_2O, 6.73% MgO and others impurities. Mechanical properties of this material is presented in table2:

Mechanical properties	Young's modulus	Poisson ratio	Thermal expansion coefficient
values	59GPa	0.218	$9.01*10^{-6}$/°C

Table2 : Mechanical properties of lead crystal

A Compressive Split Pressure Hopkison [4] which consists of an incident bar and a transmitter bar was used. The MBD lead crystal specimen was inserted between them. A strike bar produces an impact at the end of the incident bars and generates a longitudinal compressive non dispersive pulse which propagates toward the specimen. Two mounted gages on input bar and the transmitted bars are used to record the electronic signal which contains the compressive wave amplitude and tensile stress apply to the specimen respectively (see Fig.4.)
For comparison, a static loading was also applied with a conventional universal testing machine.

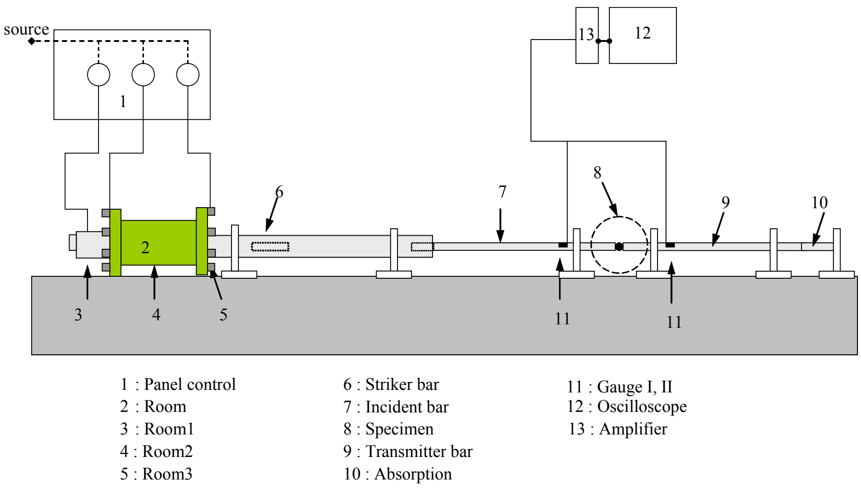


Fig. 4.Compressive Split Pressure Hopkinson Bars configuration test

Both results of static and dynamic tests are plotted Fig. 5. In addition Tuler's and Butcher's model is also presented with the best fitted constant values. According to that, Tuler and Butcher's material constants can be extracted via a curve fitting technique as $\lambda = 1.71$ and $C = 0.02652$ for the considered lead crystal MBD specimens. Different fracture mechanisms can be observed in dynamic and static tests. In Fig. 6a, lead crystal MBD specimen has been split into several pieces from center of the specimen under static loading. Fracture initiation of static fracture has been localized by optical and Scanning Electronic Microscopy (SEM) (Fig. 6b and Fig. 6c.). In this case fracture starts from a point situated on whole surface where stress concentration is located. The fracture mechanism is different for dynamic loading relative. The lead crystal MBD specimen has been broken into multiple fragments (Fig. 6d). This multifragmention is connected with to the observed scatter and increased tensile critical stress. For brittle material, Weibull's distribution [6] is traditionally proposed and described fracture strength distribution.The Weibull's distribution can be written as:

$$Ln\left[Ln\left(\frac{1}{1-P_r}\right)\right] = \beta\,Ln(\sigma) \qquad (17)$$

where, P_r and β are failure probability for each specimen and Weibull's modulus which determines the magnitude of the strength scatter distribution, respectively. The Weibull's modulus is one index to specify random fracture intensity. For high and low random fracture intensity, low and high Weibull's modulus can be observed, respectively.

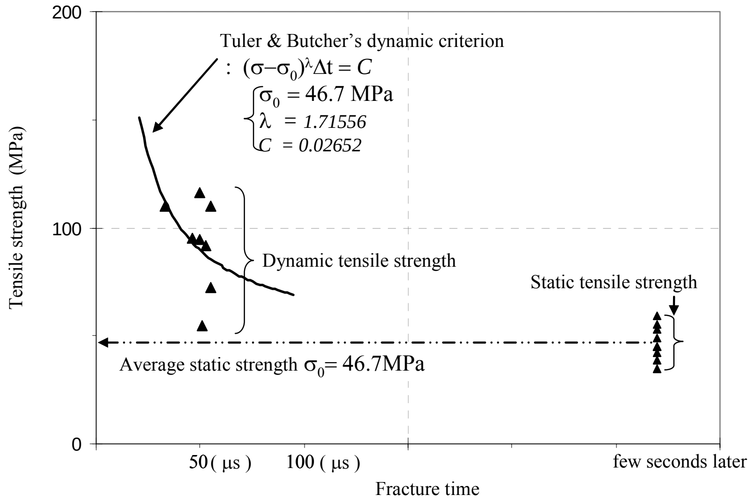
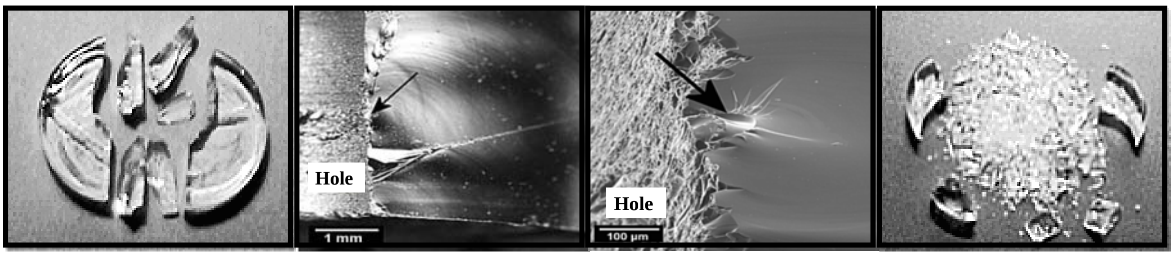


Fig. 5 Tensile strengths of lead crystal versus fracture time based on obtained experimental results (2003, J. Jeong[5])



(a) (b) (c) (d)

Fig.6. Lead crystal fracture phenomena a) General view of static loading b) Fracture initiation (optical microscopy) c) Detail of initiation site by SEM d) Multi-fragmentation under dynamic fracture of lead crystal

The Weibull's modulus for glass is generally estimated about 5 [7,8]. In accordance with the experimental results for static and dynamic experimental tests, Weibull's modulus values have been calculated as β= 5.3 and β=3.7, respectively. In Fig. 7, both static and dynamic Weibull's moduli are presented based on experimental tests. Based on experimentally obtained Weibull's modulus, the static fracture results have less random values than dynamic ones. This phenomenon has been observed by several authors [9] and is attributed to defect multi-activation under dynamic loading which leads to multi- fragentation and consequently to high scatter.

3. A DAMAGE MODEL FOR RELATIONSHIP BETWEEN DYNAMIC FRACTURE AND CRITICAL TIME

The increase of critical stress with critical time is an interesting phenomenon because we can noted that in this case fracture stress is not a characteristic of materials. Another way, is to say that this parameter is not the most appropriate to describe fracture resistance under dynamic loading.

Description of this fracture resistance can be made with the concept of damage .It is assumed that just after impact, initial materials micro-defects distributed randomly in a brittle material like glass will activated and be grow and propagate in a volume created by the impact waves generated by a spherical projectile and the target surface (Fig.1) . Damage is generated by wave propagation and the damage volume is then connected to wave velocity:

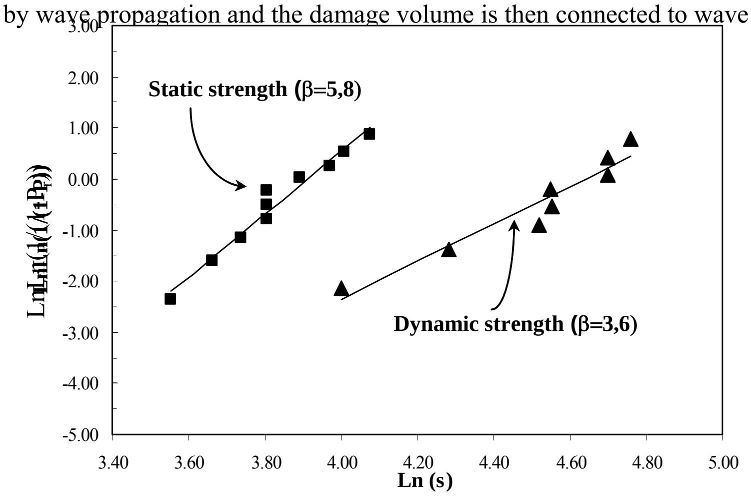


Fig. 7. Weibull's distribution for obtained static and dynamic strength experimental results for lead crystal including the Weibull's modulus β .

We can define the following damage volume:

-V_0 is the threshold volume below which there is no damage and this state corresponds to a threshold stress σ_0 and the corresponding time t_0 .

- V_i is the current volume where cumulative stresses initiate micro crack and propagation of existing micro cracks. It corresponds to current time t and an current applied stress σ .

- V_c is the critical volume (at failure) corresponding to fracture time t_c and critical stress σ_c . Fracture occurs the critical volume value is reached and consequently critical damage value. Damage D parameter is is defined as follows:

$$D = 1 - \frac{V_0}{V_i} \qquad (3)$$

If V_i is equal to V_0 , damage does not occur and it corresponds to a threshold value. Therefore D is zero. When V_i is greater than V_0 , microcracks initiate and propagate into the material before to reach critical length and density and damage can be observed. This definition of damage obeys to classical normalization : D takes a value between zero and unity. From Eq. (3), damage rate is a function of the contact volume and time as follows:

$$D = -\frac{1}{V_i}\frac{\partial V_0}{\partial t} + \frac{V_0}{V_i^2}\frac{\partial V_i}{\partial t} \qquad (4)$$

Relationship between damage rate and the stress is expressed by a classical power function:

$$\dot{D}(1-D)^n = A(\sigma - \sigma_o)^n \quad , \sigma \geq \sigma_o \qquad (5)$$

where A and n are constants depending on material and test conditions. This lead to

$$\int_{t_o}^{t_c} (\sigma - \sigma_o)^n \, dt = \left(\frac{1}{A(n+1)} \right) \left(1 - \frac{V_o^{\,n+1}}{V_i^{\,n+1}} \right) \qquad (6)$$

The equation (6) is similar to Tuler's and Butcher's relationship described before (Eq. 1). But the constant is related to damage volume process. Damage evolution versus applied stress is described in Fig. 7. D Values increase from 0.12 to 0.25 for medium loading rate obtained on DBT devices (107-237 MPa/m.sec. In this case a simple fragmentation occurs: (see Fig. 3 (a and b)). characterized by few or no crack branching. Indeed, the loading rates are not high enough to allow enhanced fragmentation with multiple crack branching. When the loading rate is in the range of 400-1050 MPa/ms using PSHB, D values are between 0.44 and 0.62. Multiple fragmentations occur with formation of radial cracks and development of tangential cracks on glass plate (see Fig. 3 (c and d)). For a loading rate greater than 1050MPa/ms, damage values are higher than 0.6 and reaches unity when projectile crosses the glass specimen.

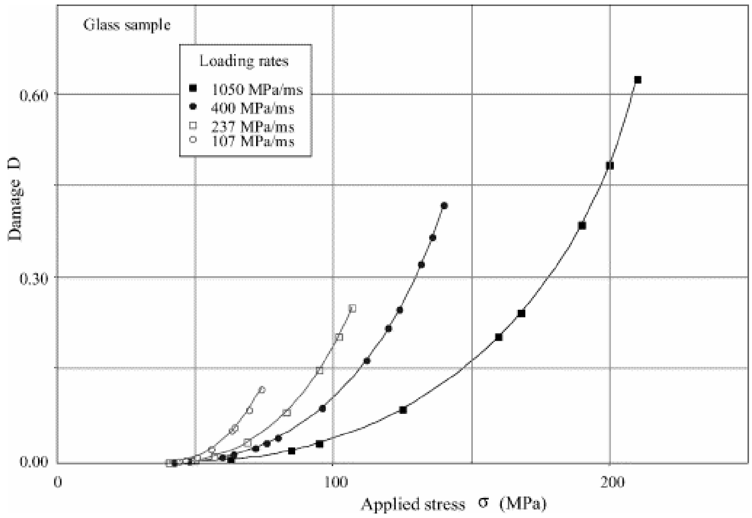


Fig. 7. Evolution of damage parameter versus applied stress at different loading rate.

CONCLUSION

Dynamic loading exhibits two particular phenomena:

Fracture stress is time depend and consequently not intrinsic to material;

Dynamic loading induces multi fragmentation and consequently increases scatter in fracture resistance.

These phenomena have been observed on Float glass and lead crystal. In order to represents evolution of fracture stress with critical time, damage concept can be used. In this case critical time represents the necessary time to build in fracture process volume where critical damage value takes place.

REFERENCE

[1] Tuler FR, Butcher BM. A criterion for the time dependence of dynamic fracture. Int. Journal of Fracture mechanic, (1968)

[2] Klepaczko JR. Dynamic crack initiation, some experimental methods and modeling. In: Klepaczko JR. editor. Cracks dynamic in metallic materials. Vienna: Springer, 1990

[3] S. Bouzid, A. Nyoung, Z. Azari, 'Fracture criterion for glass under impact loading" Int. Journal of Impact Engineering, 25 (2001) 831-845

[4] A. Nyoung, Z. Azari, G. Pluvinage, "Chronologie de la rupture statique et dynamique d'un anneau en verre float » XV ème Congrès Français de Mécanique, 2001

[5] J. Jeong, H. Adib, G. Pluvinag "Probabilité de la résistance mécanique du cristal soumis à un choc thermique", Science and Technologies, December 2003, n° 20

[6] W. Weibull, "A statistical distribution function of wide applicability" Journal of Applied Mechanical, 1951

[7] A. Nyoungue, "Comportement à la rupture des matériaux fragiles sous sollicitation dynamique", Thesis, University of Metz, France, 2001

[8] J. Gong, “Indentation toughness of ceramics: statistical analysis”, Ceramic International 2002
[9] Sang Ho Cho et al., “Strain-rate dependency of the dynamic tensile strength of rock”, International Journal of Rock Mechanics & Mining Sciences, 2003.