# Dynamic Compression Behavior of Zirconium and Iron-Based Bulk Metallic Glasses


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## ABSTRACT


In the present study, the Split-Hopkinson Pressure Bar (SHPB) was employed to perform high strain-rate compression tests on a Zr-based bulk metallic glass (Liquidmetal-1) for length-to-diameter (L/D) ratios varying from 0.5 to 2.0 and for both as-cast (i.e. fully amorphous) and annealed conditions. Ultra high-speed photography, scanning electron microscopy, and optical microscopy were utilized to examine the macroscopic and microscopic fracture surfaces. These fracture surfaces and the corresponding stress-strain curves both exhibit evidence of the presence of stress concentrations. SHPB tests were also performed on an Fe-based BMG (SAM 1651) that shows promise due to its higher hardness.

From the results of the experiments, combined with finite element simulations, a novel experimental design has been developed to eliminate the effect of stress concentrations on specimen failure. Ultra high-speed photography reveals a significant change in the fracture behavior of LM-1 and evidence of failure in the gage section of the specimen. Moreover, experiments were conducted using strain gages mounted directly to the specimen surface in order to determine accurately the stress-strain behavior of LM-1.


## INTRODUCTION

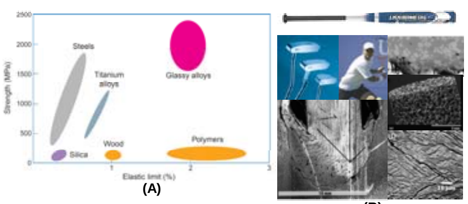


*Figure 1: Properties and Applications*
(A) BMGs exhibit very high strength and elastic strain compared to other engineering materials.
(B) Potential applications taking advantage of unique properties of BMGs

## OBJECTIVES

- Amorphous LM-1
  - Effects of L/D ratio, shear banding, flow/fracture behavior
- Annealed LM-1
  - Promote fragmentation
- Fe-based BMG (SAM 1651)
  - Exceptional hardness (13 GPa), more extensive fragmentation

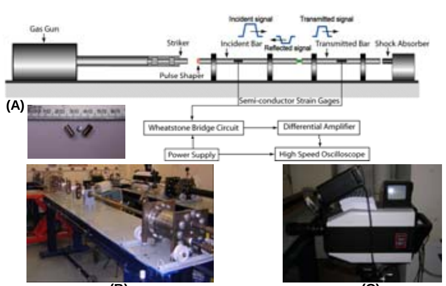


*Figure 2: (A) Schematic and (B) picture of SHPB, (C) high-speed camera*

## MATERIAL BEHAVIOR


*Figure 3: Macroscopic fracture behavior of LM-1*
(A) *As-cast specimens with L/D of 1 or 2:* Single dominant shear plane, fracture angle about 50º.
(B) *As-cast specimens with L/D of 0.5:* Single shear plane, then crushing and consolidating behavior.
(C) *Annealed specimens:* Extensive fragmentation regardless of L/D ratio.

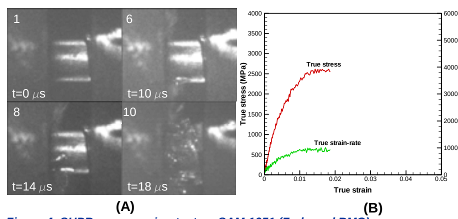


*Figure 4: SHPB compression test on SAM 1651 (Fe-based BMG)*
(A) *In-situ video:* (Frame 1) shows the undeformed specimen, (Frame 6) initial failure at the insert-specimen interface, (Frame 8) additional shear plane formation, and (Frame 10) fragmentation.
(B) *Stress-strain curve at 1000/s.* Maximum stress in Fe-based BMG: 2.7-3.3 GPa.

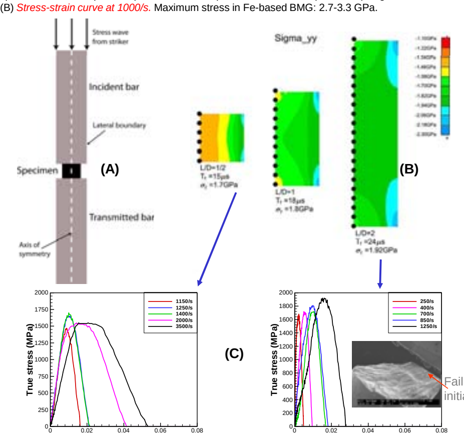


*Figure 5: Finite Element Simulation of Experiments*
(A) Schematic of finite element simulations in LS-DYNA -2D
(B) For all three specimens, a stress concentration is at the lateral boundary at the specimen/bar interfaces. This stress concentration is most sever e for the smallest L/D ratio specimens.
(C) This corresponds to the drop in peak stress and observed failure from the specimen-insert interface.

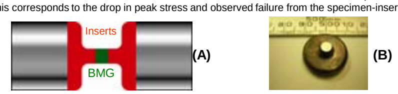


*Figure 6: Novel Experimental Setup, including (A) schematic and (B) actual inserts*

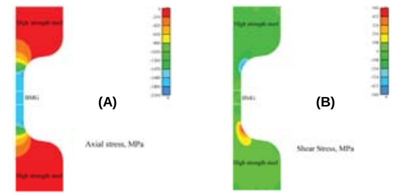


*Figure 7: Finite Element Simulations of New Experimental Setup:*
*(A) homogeneous, uniaxial stress state and (B) negligible shear stress.*

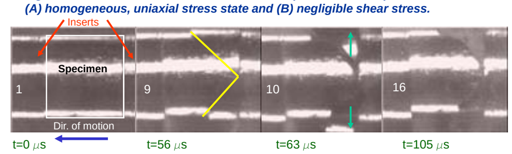


*Figure 8: In-situ Video of New Experimental Setup on As-Cast Specimen*
(Frame 1): The initially undeformed specimen is shown. (Frame 9): During loading, two planes of shear are generated in the specimen, (Frame 10) causing specimen failure. (Frame 16): The remainder of the specimen penetrates the right insert, and in doing so, demonstrates self-sharpening behavior.

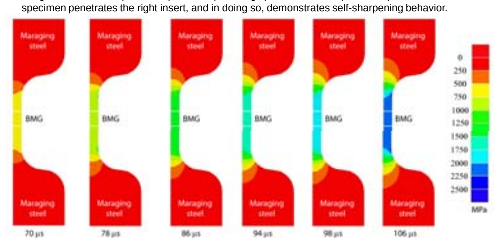


*Figure 9: Evolution of stresses in New Experimental Setup*
Finite element simulations reveal equilibrium is reached well before specimen failure.

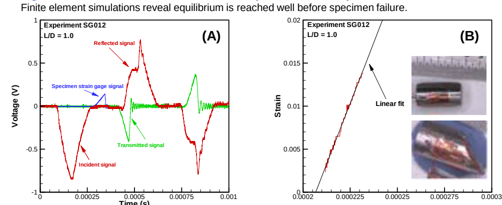


*Figure 10: Experimental Validation of New Experimental Setup*
(A) Strain histories from strain gages on specimen, incident bar, and transmitted bar.
(B) Calculated strain vs. time profile shows constant strain-rate.

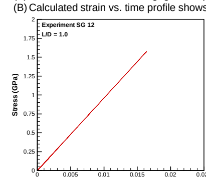


*Figure 11: Calculated stress-strain curve*
(A) The stress-strain curve was assumed to be linear elastic to failure.
(B) The assumed elastic modulus was 96 GPa, consistent with other experiments conducted.

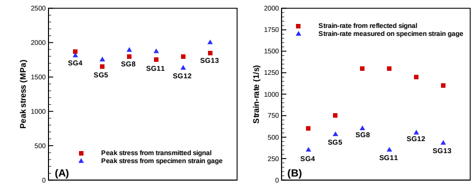


*Figure 12: Comparison of stresses and strain-rates from specimen and bars*
(A) Stresses from specimen strain gage, transmitted signal are similar
(B) Strain-rates from specimen strain gage, reflected signal are not similar (deformation of inserts)

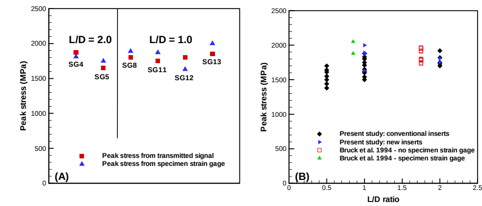


*Figure 13: Effect of L/D on Peak Stresses*
(A) Peak stress appears to be independent of L/D ratio
(B) Comparison of results with previous work performed by Bruck (1994)

## SUMMARY

- The as-cast LM-1 fails via shear band formation and slip; the annealed LM-1 fails via extensive fragmentation.
- Finite element simulations show a non-uniform stress state due to stress concentrations at specimen-bar interface.
- A new experimental design has been developed to provide a uniform stress state in the specimen.
  - Failure occurs in the gage section of the specimen.
  - Equilibrium conditions are not compromised because of new inserts.
  - Strain gage experiments reveal constant strain-rate and no effect of L/D ratio on peak stress of LM-1.
  - Stress from transmitted signal and specimen strain gage are similar.
  - Stress from reflected signal and specimen strain gage are not similar.
    - Due to deformation of the new inserts

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| | |
|---|---|
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