Final Report Information
(Aug. 1, 1996 – Sept. 30, 1998)

ONR GRANT INFORMATION

1. Grant Title: Dynamic Failure Behavior of Naval Structural Steels

2. Performing Organization: Georgia Tech Research Corporation/
Georgia Institute of Technology

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7. ONR Scientific Officer: Dr. Yapa D. S. Rajapakse

List of Publications/Reports/Presentations

1. **Papers published in and submitted to referred journals:**

1. M. Zhou, A. J. Rosakis and G. Ravichandran, Dynamically Propagating Shear Bands in Impact-loaded Prenotched plates, I - Experimental Investigations of Temperature Signatures and Propagation Speed, *J. Mech. Phys. Solids*, **44**, pp.981-1006, 1996.
2. M. Zhou, G. Ravichandran and A. J. Rosakis, Dynamically Propagating Shear Bands in Impact-loading Prenotched plates, II - Numerical Simulations, *J. Mech. Phys. Solids*, **44**, pp.1007-1032, 1996.
3. M. Zhou and R. J. Clifton, "Dynamic Ductile Rupture under the Conditions of Plan Strain, *Int. J. Impact Engng.*, **19**, pp.189-206, 1997.
4. M. Zhou, Effects of Microstructure on the Resistance to Shear Localization for a Class of Metal Matrix Composites, *Fatigue and Fracture of Engineering Materials Structures*, **21**, pp. 425-438, 1998.
5. M. Zhou, A. J. Rosakis and G. Ravichandran, On the Growth of Shear Bands and Failure-Mode Transition in Prenotched Plates: A comparison of singly and doubly notched specimens, *Int. J. Plasticity*, **14**, pp.435-451, 1998.
6. M. Zhou and R. J. Clifton, Dynamic Constitutive and Failure Behavior of a Two-phase Tungsten Composite, *Journal of Applied Mechanics*, **64**, pp. 487-494, 1997.
7. M. Zhou, The Growth of Shear Bands in Composite Microstructures, *Int. J. Plasticity*, **14**, pp. 733-754, 1998.
8. K. Minnaar and M. Zhou, An Analysis of the Dynamic Shear Failure Resistance of Structural Metals, *J. Mech. Phys. Solids*, **46**, 1998.
9. S.W. Park, M. Zhou and D. R. Veazie, "Time-resolved Impact Response and Damage of Fiber-reinforced Composite Laminates", submitted to *Journal of Composite Materials*, 1998.
10. S. W. Park and M. Zhou, "Separation of Elastic Waves in Split Hopkinson Bars using One-point Strain Measurements", submitted to *Experimental Mechanics*, 1998.

2. **Conference papers, thesis, and papers to be submitted:**

11. K. Minnaar, Comparison and Analyses of the Dynamic Shear Failure Resistance of Structural Metals, M.S. Thesis, Georgia Institute of Technology, Nov. 1997;
12. K. Minnaar and M. Zhou, Microstructural Failure Mechanisms during Dynamic Shear Deformation of Structural Metals, manuscript in preparation and to be submitted to *Int. J. Plasticity*, 1998.
13. S. W. Park and M. Zhou, (1998), "Ultrasonic Characterization of Impact-Induced Damage in Fiber-reinforced Laminated Composites", Fifth International Conference on Composites Engineering (ICCE/5), pp. 711-712, July 5-11, Las Vegas, NV.
14. S. W. Park and M. Zhou, (1998), "An Improved Analysis Technique for Impact Experiments on Composites using the Split Hopkinson Pressure Bar", Fifth International Conference on Composites Engineering (ICCE/5), pp. 1021-1022, July 5-11, Las Vegas, NV.
15. M. Zhou, A. J. Rosakis and G. Ravichandran, "Adiabatic Shear Band Formation in Asymmetrically Impacted Prenotched Plates - An Investigation of Temperature Signatures", *Materials Instabilities: Theory and Application*, AMD-Vol. **183**/MD-Vol. **50**, pp. 35-49, Nov., 1994.
16. M. Zhou, R. J. Clifton and A. Needleman, "Shear Bands in Pressure-shear Plate Impact", *Proc. 13th Army Symposium on Solid Mechanics*, pp. 117-135, Aug. 1993, Plymouth, MA.

17. A. J. Rosakis, G. Ravichandran and M. Zhou, "Real-Time Experimental Observations of Two-dimensional Dynamic Shear Band Growth", AMD-Vol. **200**/MD-Vol. **57**, pp. 95-100, Plastic and Fracture Instabilities in Materials, 1995.
18. A. J. Rosakis, G. Ravichandran and M. Zhou, "Dynamically Growing Shear Bands in Metals: A study of Transient Temperature and Deformation Fields", *Proc. IUTAM Symposium on Nonlinear Analysis of Fracture*, September 1995, Cambridge, England.

3. Presentations

a. Invited:

1) M. Zhou, "*Dynamic Shear Failure Resistance of Structural Metals*", Symposium on the Dynamic Deformation and Failure Mechanics of Materials, Caltech, Pasadena, CA, May 22-24, 1997.

b. Contributed:

1) S. W. Par and M. Zhou, Impact response, Damage and Residual Strength of Fiber-reinforced laminate Composites, Fifth International Conference on Composites Engineering (ICCE/5), July 5-11, Las Vegas, NV, with S. W. Park.
2) M. Zhou, *Dynamic Failure Resistance of Structural Materials*, Office of Naval Research 6.1/6.2 Workshop at Naval Surface Warfare Center-Carderock, MD, May 5-7, 1998
3) J. Zhai and M. Zhou, *Numerical Simulations of Dynamic Failure in Structural Composites*, 13th US National congress of Applied Mechanics, Gainesville, FL, June 21-26, 1998.
4) K. Minnaar and M. Zhou, *Ductile Shear Failure during Deformation Localization*, Symposium on Ductile Damage and Failure Mechanics, McNU'97, June 29- July 2, 1997, Northwestern University, Chicago, IL.
5) M. Zhou, *The growth of shear bands in composite microstructures*, ASME Winter Annual Meeting, Atlanta, GA, Nov., 1996;
6) M. Zhou, *Numerical Analyses of the Influence of Microstructural Changes on Shear Localization in Tungsten Composites*, 14th Army Symposium on Solid Mechanics, Myrtle Beach, SC, October, 1996.
7) M. Zhou, *Effect of microstructure on propagation of shear bands*, ASME Summer Annual Meeting, Baltimore, MD, June 1996;

List of Honors/Awards

Name of Person Receiving award	Recipients institution	Name, sponsor and purpose of award
Min Zhou	Georgia Institute Technology	IMM fellowship for 1997 IMM/NSF Young Investigator Symposium

Summary
Publications/Patents/Presentations/Honors/ Participants
(Number Only)

			ONR Supported	Non ONR
a.	Number of Papers Submitted to Refereed Journals but not yet published:		3	3
b.	Number of Papers Published in Refereed Journals:		8	2
c.	Number of Books or Chapters Submitted but not yet Published:		1	0
d.	Number of Books or Chapters Published:			
e.	Number of Printed Technical Reports & Non-Refereed Papers:		3	4
f.	Number of Patents Filed:			
g.	Number of Patents Granted:			
h.	Number of Invited Presentations at Workshops or Prof. Society Meetings:		1	0
i.	Number of Contributed Presentations at Workshops or Prof. Society Meetings:		7	4
j.	Honor/Awards/Prizes for Contract/Grant Employees:		1	
k.	Number of Graduate Students and Post-Docs Supported at least 25% this year on contract grants:		2	4
	Grad Students:	TOTAL	1	
		Female		
		Minority		
	Post Doc:	TOTAL	1	1
		Female		
l.	Number of Female or Minority PIs or Co-PIs			
		New Female		
		Continuing Female		
		New Minority		
		Continuing Minority	1	

Final Report for ONR Project Entitled

DYNAMIC FAILURE BEHAVIOR OF NAVAL STRUCTURAL STEELS

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August 1, 1996 – September 30, 1998

Project Objective

The objective of this two-year research is to

1. Characterize the dynamic constitutive behavior of structural metals including HY-80, HY-100, HSLA-80, HSLA-100, 4340 and Ti-6Al-4V;
2. evaluate the factors that determine their dynamic shear failure resistance; and
3. obtain experimental quantification of the failure resistance of these materials.

Summary of Approach and Accomplishments

A combined experimental and numerical approach has been employed in the investigation. The work carried out consists of experimental characterization of failure behavior and numerical simulations. Specific accomplishments are:

1. The responses of the above materials over a wide range of strain rate (of 10^{-3} to 10^{4} s^{-1}) have been characterized;
2. The dynamic shear failure resistances of these materials have been experimentally characterized;
3. A novel Cohesive Finite Element Method (CFEM) has been developed for the modeling of dynamic shear failure, accounting for microscopic rupture as well as thermomechanical response. Numerical simulations have been carried to illustrate the failure behavior and failure mechanisms. This accomplishment exceeded the initial scope of tasks.

The materials are tested in the as-received condition from manufacturers. Their properties meet the military specifications. Our effort focused on the evolution of the load-carrying capacity of these materials during shear band development *and* associated microscopic changes. The work so far provided data on the failure behavior of these materials. The data is useful for designers of naval vessels. The findings have been reported in Minnaar and Zhou (1998).

A compression Kolsky bar apparatus is used to achieve well-controlled dynamic shear deformation. This configuration is illustrated in Fig. 1. The specimen is axisymmetric and hat-shaped. Upon impact loading, the specimen is subjected to compression between its two end surfaces. The compression causes shear deformation in the ligament between the solid section and its hollow annulus section. The intense shear in the ligament provides the conditions needed to produce shear band initiation and propagation from the specimen corners. This configuration allows shear band development to different stages to be obtained by choosing the amount of deformation Δ allowed through the use of stoppers with different thickness values. The nominal stress-strain relations are used to evaluate failure progression and load-carrying capacities of different materials.

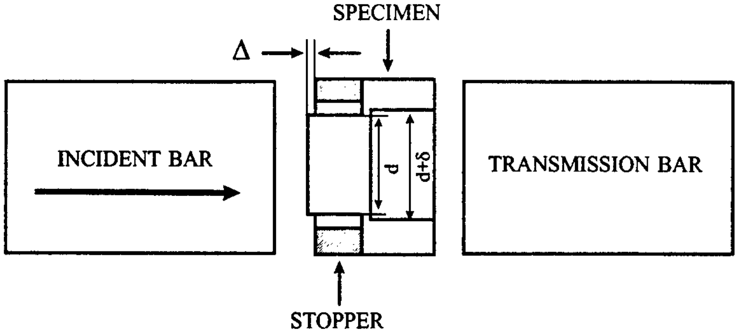


Fig. 1 Dynamic Shear Failure Experiment

Constitutive Response and Failure Parameters

The constitutive behaviors of the materials over a wide range of loading have been analyzed using dynamic compression and quasistatic tension. The combination of dynamic and quasistatic experiments are chosen to yield a complete set of experimental characterization required for cohesive finite element simulations. The stress-strain curves for the five materials over the strain rate range of 10^{-3}-10^{4} s^{-1} are shown in Fig. 2(a-e). A comparison of the dynamic responses of the materials for similar strain rates between $2.1\text{-}2.4\times10^{4}$ s^{-1} is given in Fig. 2(f). The curves show that like their similar quasistatic yield strengths and ultimate tensile strengths, the steels have similar dynamic constitutive behaviors in the strain rate range of 10^{2} - 10^{4} s^{-1}. The similar quasistatic and dynamic responses indicate that the steels have nearly the same rate-sensitivities in the strain rate range analyzed. It can be seen in Fig. 2(f) that the steels also have nearly the same rate of strain hardening. The similar constitutive behavior is in contrast to their significantly different shear failure behavior observed. This difference highlights the influence of microscopic damage and will be further discussed later in this report.

Ti-6Al-4V has a much stronger rate-sensitivity than those of the steels. In addition, its rate of strain hardening is slightly higher. Despite these factors, this material is more susceptible to shear banding and ductile rupture than the steels, as suggested by the precipitous drops in stress at strains of approximately 0.2. Postmortem analysis revealed that the shear bands occurred along plane approximately 45° from the loading axis. This is inconsistent with the understanding that strong rate-sensitivity and higher strain hardening enhance resistance to shear localization, indicating factors other than rate-sensitivity play a more dominant role in determining shear failure under the conditions analyzed. The high rates of rate sensitivity and strain hardening are in contrast to its high susceptibility to shear failure. This observation further reinforces our conclusion that thermomechanical constitutive response along does not fully determine the dynamic shear failure of structural metals. Instead, microscopic damage accompanying localized deformation plays a significant role and must be considered. The rate-dependence of the material behaviors is characterized in Fig. 3.

Evolution of Stress-carrying Capacity Throughout Deformation and Failure

The nominal shear stress-strain curves obtained from shear failure experiments for five materials are shown in Fig. 4(a-e). The stress and strain are average values in the specimen ligament. The precipitous drops in shear stress signifies the loss of stress-carrying capacity associated with shear failure development. The increase in stress following the drop on each curve results from the contact of the incident bar and the stopper. It signifies the cessation of deformation in the specimen. To facilitate comparison, the curves for all five materials for a stopper thickness of 2.0 mm ($\gamma_{max} = 4.3$) are shown in

Fig. 4(f). Clearly, all materials show a total loss of stress-carrying capacity indicated by the drop of stress to near zero levels. The shape of the curves indicate that the strains at which materials lose all of their stress-carrying capacities increase in the order Ti-6Al-4V → HY-80 → HY-100 → HSLA-80 → 4340. The critical strain level for Ti-6Al-4V is approximately 1.6. Significantly lower than those of the steels. Ti-6Al-4V does not display a period of gradual decrease of stress. Instead, a rapid loss of stress is observed immediately after the onset of localization. The steels, on the other hand, show gradual softening preceding the rapid losses of load-carrying capacity, indicating higher resistance to shear failure.

Microscopic Observations

The deformed microstructures of the steels at different nominal shear strain levels have been analyzed to determine the failure parameters in the cohesive finite element models. Consistent with the stress-strain profiles, micrographs indicate significantly different levels of resistance to shear banding and rupture. The martensitic microstructure of HY-100 makes it more susceptible to the development of intensely localized shear bands. However, its earlier development of localization does not necessarily result in early loss of stress as seen in Fig. 4. Instead, significant loss of strength follows more closely the subsequent ductile rupture of materials.

The deformed microstructures of the steels at nominal shear strain levels of 2.0 and 2.5 are shown in Fig. 5. This series of pictures illustrates the progression of localization and rupture in each material. Consistent with the stress-strain profiles, the micrographs indicate significantly different levels of resistance to shear banding and rupture. The martensitic microstructure of HY-100 makes it more susceptible to the development of intensely localized shear bands. However, its earlier development of localization does not necessarily result in early loss of stress as seen in Fig. 4. Instead, significant loss of strength follows more closely the subsequent ductile rupture of materials.

To quantify the extent of shear localization and rupture, the lengths of shear bands and cracks following the shear bands are compared, see Fig. 6. These two lengths increase with the nominal shear strain inside the ligament. For each of the steels, there is an appreciable difference in the shear band length and the crack length, suggesting development of rupture after localization of strain. For Ti-6Al-4V, the shear band length and the rupture length are very close to each other. This lack of difference for the titanium alloy indicates the near simultaneous occurrence of localization and rupture. Partly because of this rapid development of rupture, Ti-6Al-4V exhibits a much higher degree of susceptibility to the loss of stress-carrying capacity than those of the steels.

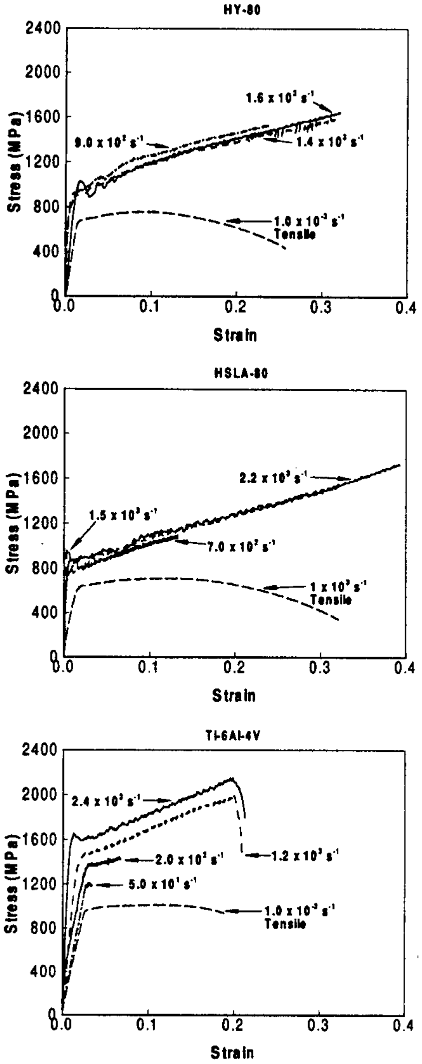


Fig. 2 Dynamic Constitutive Response of Five Structural Metals

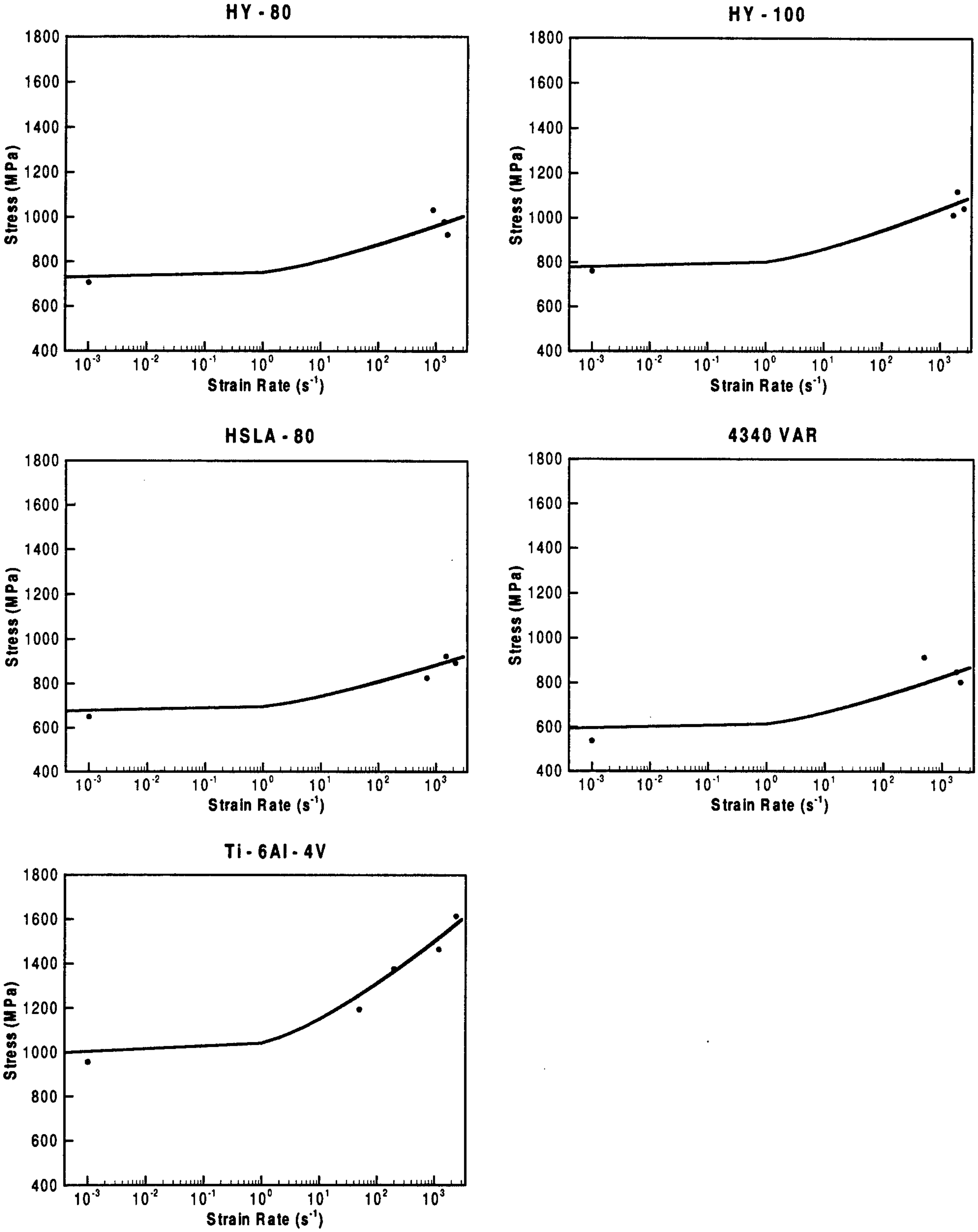


Fig. 3 Characterization of the rate-dependence of the materials

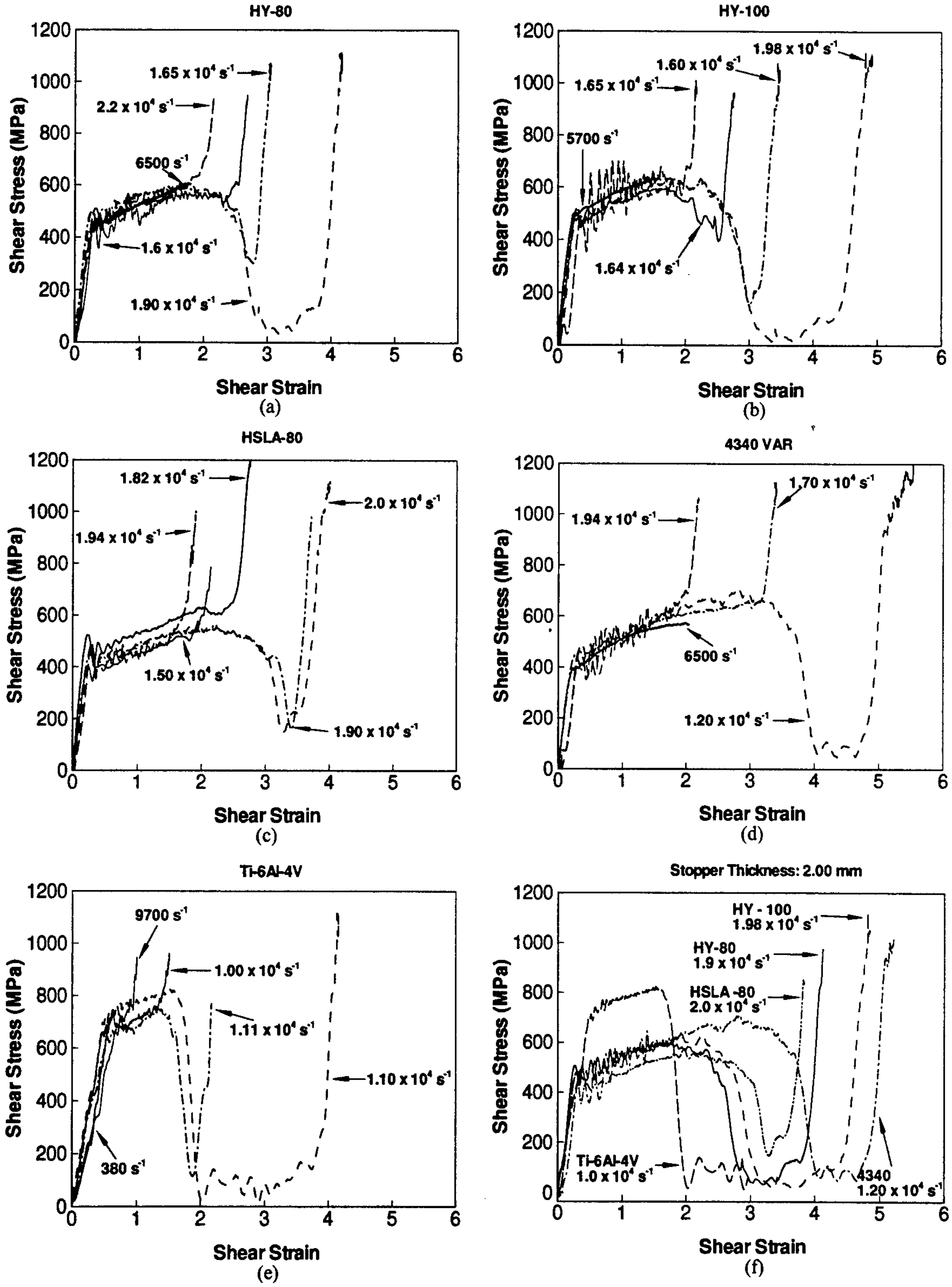
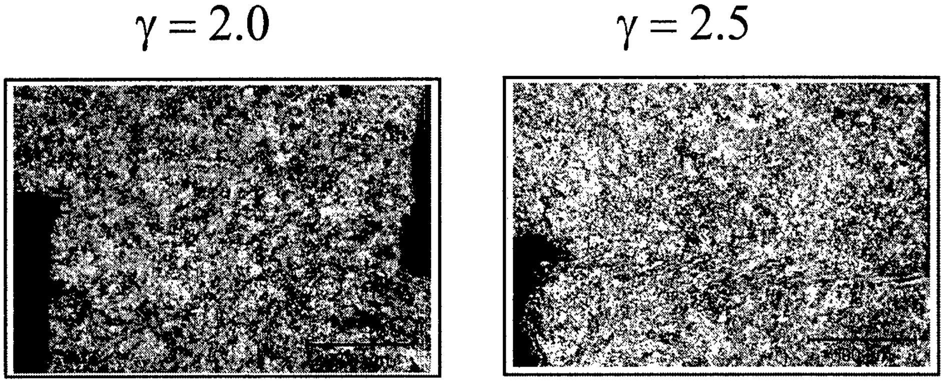
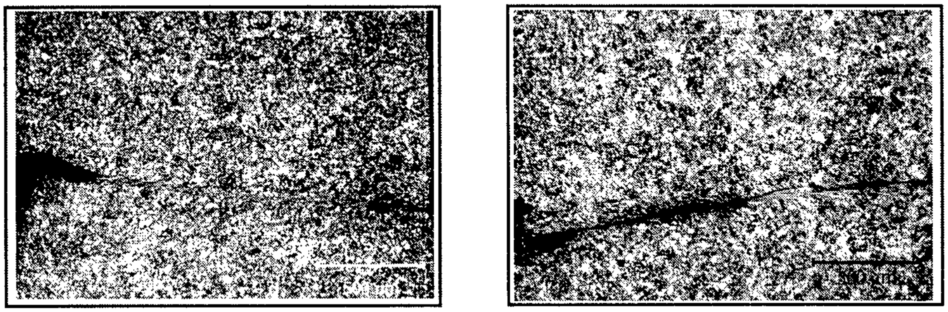


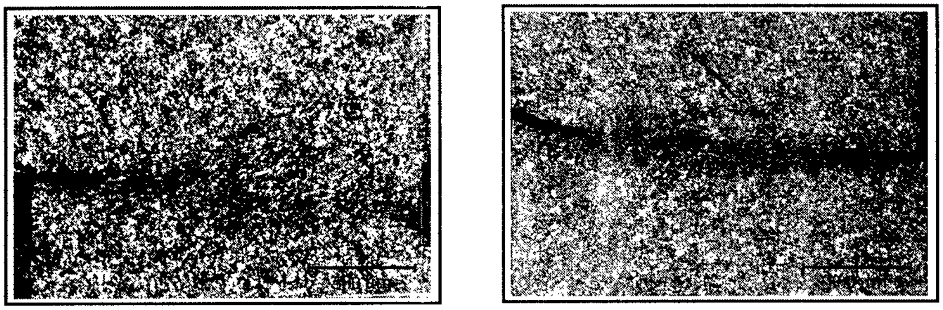
Fig. 4 Evolution of Stress-Carrying Capacity for Five Materials during Dynamic Shear Failure



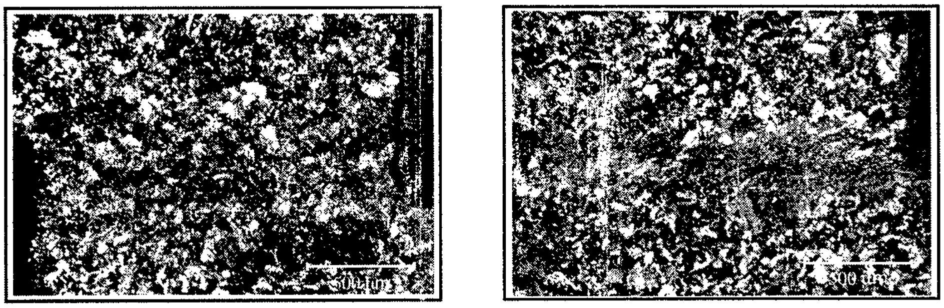
(a) HY-80



(b) HY-100

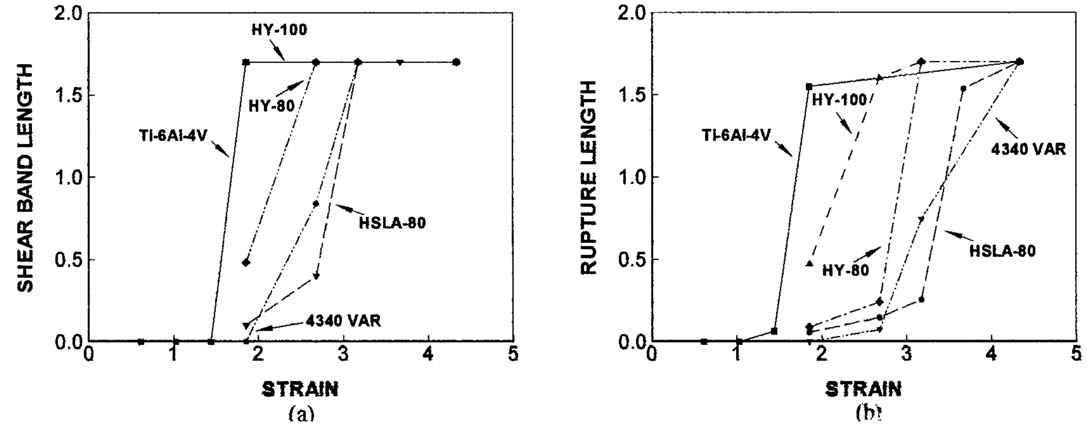


(c) HSLA-80



(d) 4340 VAR

Fig. 5 Morphologies of Strain Localization and Ductile Rupture at γ =2.0 and 2.5 for HY-80,(b) HY-100, (c) HSLA-80, and (d) 4340VAR steels



(a) (b)

Fig. 6 Shear Band and Rupture Lengths as Functions of Shear Deformation (a) Shear Band Length, (b) Rupture Length

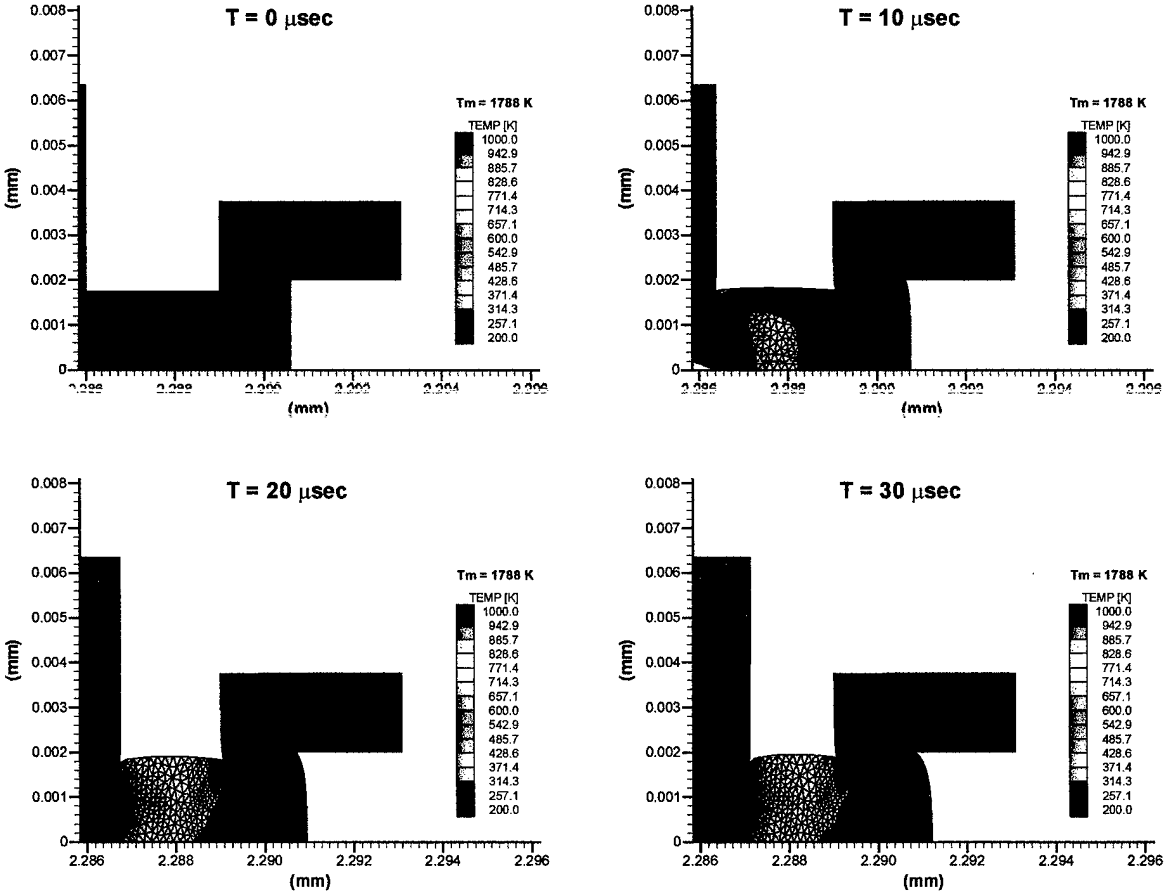


Fig. 7 Numerical simulations of the dynamic shear failure experiment (Distribution of Temperature and Mesh Adaptation)

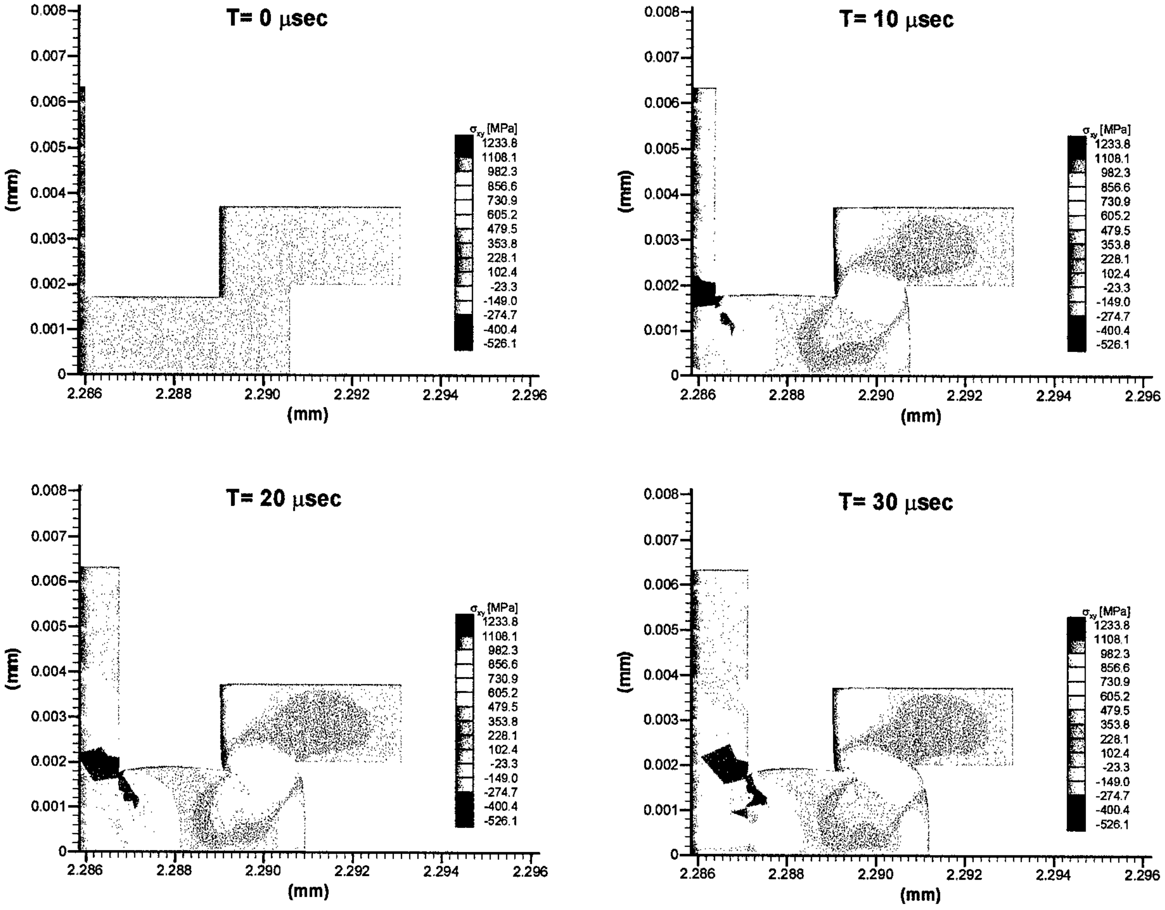


Fig. 8 Numerical simulations of the dynamic shear failure experiment
(Distribution of Shear Stress)

Cohesive Finite Element simulations:

Numerical simulations have been carried out using the CFEM approach developed, accounting for thermomechanical deformation and progressive rupture. The framework of analysis is fully dynamic and uses cohesive finite element to describe stress- and strain-controlled failure. Automatic mesh adaptation is used to resolve high gradient of deformation and arbitrary fracture paths. A series of deformation states during a calculation is shown in Fig. 7 and Fig. 8. These pictures show the stages of deformation, strain location, and rupture. The capability developed and the novel approach for complete account of ductile and brittle failure goes beyond the originally proposed scope of investigation.

The findings of this research are:

1) Despite their significantly different static properties such as yield strength and hardness, chemical compositions and heat treatment, the steels (HY-80, HY-100, HSLA-80, HSLA-100, and 4340) have very similar dynamic constitutive behaviors in the strain rate range of 10^2 - 10^4 s^{-1}.
2) There is a relatively large variation in the shear failure resistance among the steels, as measured by the stress strain curves and the critical shear strain for failure. This is in contrast to their similar thermomechanical constitute behaviors observed;

3) While the steels are also relatively rate-insensitive, the titanium alloy (Ti-6Al-4V) shows much stronger rate-sensitivity in the same strain rate regime. However, despite this higher rate-sensitivity, Ti-6Al-4V is more susceptible to shear banding and rupture than the steels. This finding is in contrast to the fact that strain rate dependence enhances resistance to shear localization;
4) Based on an approximate shear localization model of Grady (1994) which accounts for the strain sensitivity, thermal softening and heat conduction, very similar band dissipation energy (G_s) and shear band toughness (K_s) values are predicted for the steels, see Table 1. The toughness does not include the influence of microscopic damage and rupture inside shear bands on the stress-carrying capacity of materials. The significantly different shear failure behaviors of the steels observed demonstrate that rupture inside shear bands is an important part of the failure process that should to be considered in evaluating failure.
5) A Cohesive Finite Element approach has been developed allowing for full account of deformation and rupture. This provides a novel capability for quantifying the shear failure resistance of structural metals.

Table 1 Dissipation energy and shear band toughness

Material	Flow Stress (MPa)	Dissipation Energy Γ_s (KJ/m^2)	Shear Band Toughness K_s (MPa$\sqrt{m}$)
HY-80	1460	125.2	142.221
HY-100	1530	120.9	139.745
HSLA-80	1280	138.2	149.414
4340VAR	1450	125.9	142.588
Ti-6Al-4V	2000	3.935	18.861

Suggested Future Activities:

The cohesive finite element method developed allow simulation of both the deformation and failure processes in the metals. The actual experimental configuration should be accounted for as well as measured material properties. The modeling should provide full account for the effects of inertia, finite deformation kinematics, strain rate hardening, thermal softening and heat conduction. The novel capability will allow for a complete quantification of the factors influencing quantifying dynamic shear failure resistance of structural metals.

Relevance to the Navy:

This research is relevant to the design of naval structures in maximizing the structural integrity for various service conditions. This contribution is reflected in four ways: (1) the shear failure resistance comparison and shear failure toughness measure developed provides guidance for the selection of appropriate materials; (2) understanding of how shear failure propagates in materials will enable optimization of structural design to minimize damage; and (3) understanding gained will provide suggestion for the revision and improvement of naval structural metals and contribute to the development of more failure-resistant materials.

Refereed Publications:

1. M. Zhou, A. J. Rosakis and G. Ravichandran, Dynamically Propagating Shear Bands in Impact-loaded Prenotched plates, I - Experimental Investigations of Temperature Signatures and Propagation Speed, *J. Mech. Phys. Solids*, **44**, pp.981-1006, 1996.
2. M. Zhou, G. Ravichandran and A. J. Rosakis, Dynamically Propagating Shear Bands in Impact-loading Prenotched plates, II - Numerical Simulations, *J. Mech. Phys. Solids*, **44**, pp.1007-1032, 1996.

3. M. Zhou and R. J. Clifton, "Dynamic Ductile Rupture under the Conditions of Plan Strain, _Int. J. Impact Engng._, **19**, pp.189-206, 1997.
4. M. Zhou, "Effects of Microstructure on the Resistance to Shear Localization for a Class of Metal Matrix Composites", _Fatigue and Fracture of Engineering Materials and Structures,_ **21**, pp. 425-438, 1998.
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6. M. Zhou, A. J. Rosakis and G. Ravichandran, On the Growth of Shear Bands and Failure-Mode Transition in Prenotched Plates: A comparison of singly and doubly notched specimens, _Int. J. Plasticity_, **14**, pp.435-451, 1998.
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7. K. Minnaar, Comparison and Analyses of the Dynamic Shear Failure Resistance of Structural Metals, M.S. Thesis, Georgia Institute of Technology, Nov. 1997;
8. K. Minnaar and M. Zhou, An Analysis of the Dynamic Shear Failure Resistance of Structural Metals, _J. Mech. Phys. Solids_, **48**, in press and to appear, 1998.
9. K. Minnaar and M. Zhou, Microstructural Failure Mechanisms during dynamic Shear Deformation of Structural Metals, manuscript in preparation and to be submitted to _Int. J. Plasticity_, 1998.
10. S. W. Park and M. Zhou, "Separation of Elastic Waves in Split Hopkinson Bars using One-point Strain Measurements", submitted to _Experimental Mechanics_, 1998.

Non-referred Publications:

1. S. W. Park, D. R. Veazie and M. Zhou, Characterization of Impact Damage and Residual Strength of Structural Composites, _Proceedings of the 12th ASCE Engineering Mechanics Conference_, pp. 1311-1314.
2. Minnaar, Comparison and analysis of Dynamic Shear Failure Behavior of Structural Metals, Georgia Tech M.S. thesis, 1997.

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13. ABSTRACT ***(Maximum 200 words)***

The objective of this two-year research is to (1) characterize the dynamic constitutive behavior of structural metals including HY-80, HY-100, HSLA-80, HSLA-100, 4340 and Ti-6Al-4V; (2) evaluate the factors that determine their dynamic shear failure resistance; and (3) obtain experimental quantification of the failure resistance of these materials. A combined experimental and numerical approach has been employed in the investigation. The work carried out consists of experimental characterization of failure behavior and numerical simulations. Specific accomplishments are: (1) the responses of the above materials over a wide range of strain rate (of 10^{-3} to 10^{4} s^{-1}) have been characterized; (2) the dynamic shear failure resistances of these materials have been experimentally characterized; (3) a novel Cohesive Finite Element Method (CFEM) has been developed for the modeling of dynamic shear failure, accounting for microscopic rupture as well as thermomechanical response. Numerical simulations have been carried to illustrate the failure behavior and failure mechanisms. This accomplishment exceeded the initial scope of tasks.

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