Seismic Resilience of ASTM Structural Steel Exposed to Fire Hazards through Ultra-Low Cycle Fatigue Loading

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Background: Fire Hazards in Structures

Oakland bridge collapse, California, 2007 (PC: Aziz)

Collapse of truss bridge, Tempe, 2020 (PC: Fox News)

World Trade Center tragedy, 2001 (PC: Wikimedia Commons/Robert)

Bridge Fire vs. Building Fire

- ✓ Building safety is achieved through active (e.g., sprinklers) and passive fire protection systems (e.g., fire insulation).
- ✓ Bridges are more susceptible to fire damage due to the lack of specific fire safety provisions for bridges (open-air structures).
- ✓ Bridge fires are more intense due to hydrocarbon fires from trucks or automobiles involved in collision.

Facts and Figures:

- ✓ Bridges are 3 times more likely to collapse due to fire than earthquakes (NYDOT survey).
- ✓ As per a 2022 National Fire Prevention Association (NFPA) report, 522,500 structural fires were recorded in the US, resulting in 14,630 civilian casualties and $15 billion in property damage.

Research Questions

The present study aims to address two research questions:

a) What is the earthquake resilience of structural steels exposed to fire hazards?

b) How do the underlying microstructural changes affect the macroscale behavior of the structural steels?

Project Goals and Objectives

Goal: To investigate the ultra-low cycle fatigue (ULCF) behavior of ASTM A36 structural steels after exposure to fire.

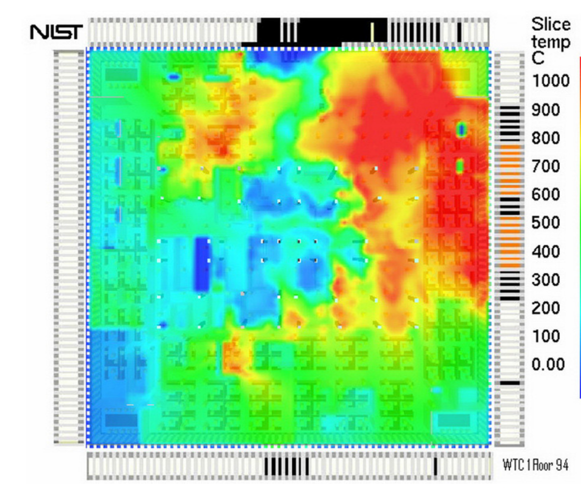
Objectives: (a) To understand the influence of heat-treatment temperature and cooling methods on the ULCF behavior of notched cylindrical steel specimens.

b) To investigate the effect of microstructural changes on the ULCF behavior of heat-treated structural steels.

Methodology

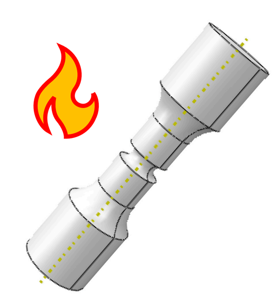
Step 1: Heat treatment

- ✓ Fully developed structural fires reach gas temperatures averaging ~1000˚C (FEMA).
- ✓ NIST estimated the maximum gas temperature on the 94th floor of WTC to be 1000˚C.
- ✓ Post-fire mechanical properties remain unaffected up to 600˚C.



Temperature profile of the 94th floor of the World Trade Center (PC: NIST)

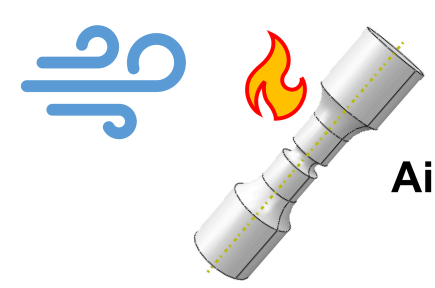
Temperatures: 600˚C, 800˚C, and 1000˚C.



Muffle Furnace

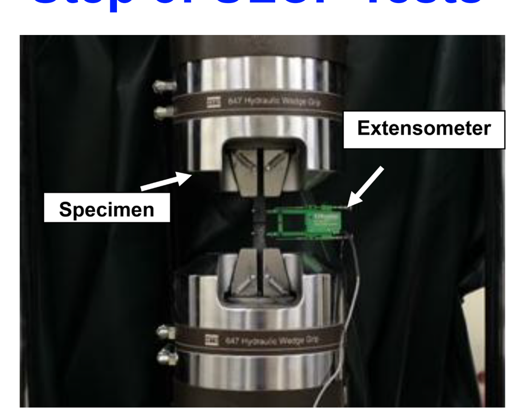
Step 2: Cooling methods

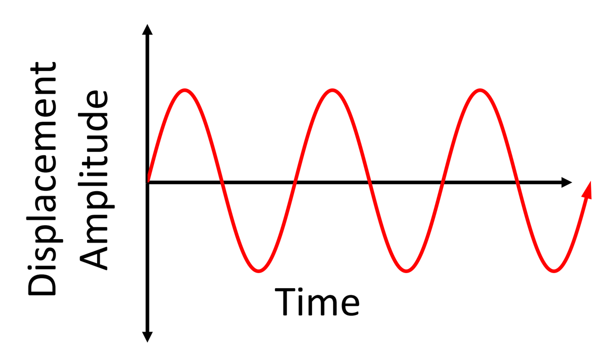
Water Cooling (WC)

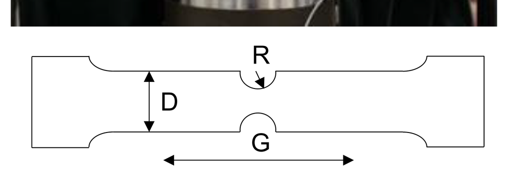


Air Cooling (AC)

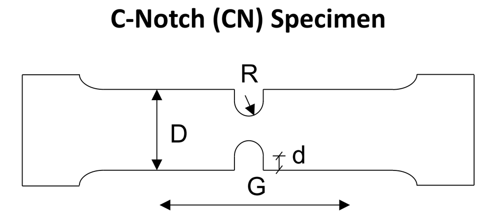
Step 3: ULCF Tests





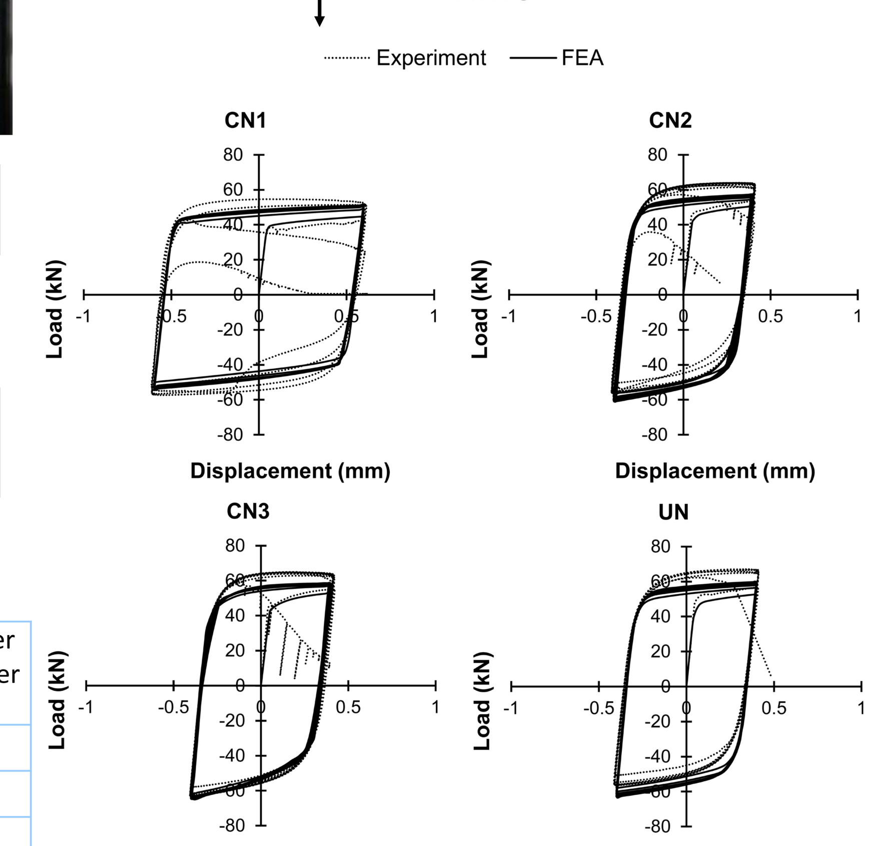


C-Notch (CN) Specimen



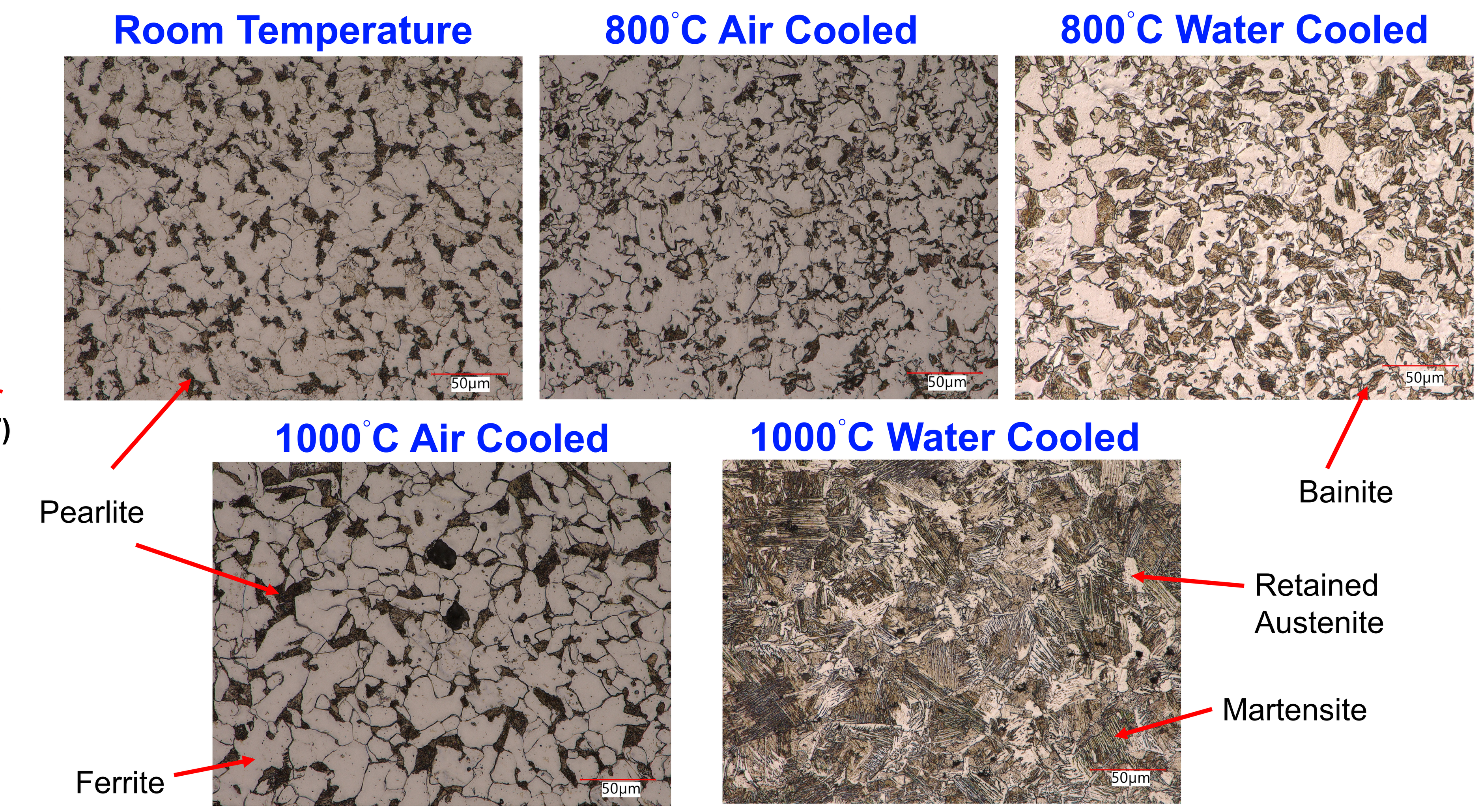
U-Notch (UN) Specimen

Notch	Notch radius (R)	Notch depth (d)	Cylinder diameter (D)
	(mm)	(mm)	(mm)
CN1	1	-	12
CN2	2	-	14
CN3	3	-	16
UN	1	1	14



Typical load-displacement behavior under ULCF loading

Microstructure



Results

ULCF cycles to failure

Notch	Control	600˚C				800˚C				1000˚C			
		AC	Change (%)	WC	Change (%)	AC	Change (%)	WC	Change (%)	AC	Change (%)	WC	Change (%)
CN1	14	16	14.28	11	-21.43	13	-7.14	1	-92.86	14	0	4	-71.43
CN2	12	18	50	19	58.33	28	133.33	2	-83.33	20	66.67	2	-83.33
CN3	15	23	53.33	20	33.33	23	53.33	1	-93.33	14	-6.67	7	-53.33
UN	10	12	20	12	20	15	50	1	-90	15	50	1	-90
Avg.			34.4		22.56		57.38		-89.88		27.5		-74.52

- ✓ ULCF life reduced by ~90% and ~75% due to water cooling from 800˚C and 1000˚C.
- ✓ Average ULCF life increased when exposed to 600˚C irrespective of cooling method.
- ✓ ULCF life mostly remains unaffected when air-cooled from 800˚C and 1000˚C.

Conclusions

1. Significant lath martensite was observed in water-cooled steel from 1000˚C, resulting in increased strength and reduced ductility.
2. Bainite formed when steel was water-cooled from 800˚C, which resulted in increased strength but reduced ductility.
3. Pearlite and ferrite were observed in the steel microstructure at room temperature.
4. Grain and pearlite colony sizes decreased when steel was air-cooled from 800˚C.
5. Grain and pearlite colony sizes increased when steel was air-cooled from 1000˚C.

Acknowledgement

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