ARTISTE2025

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Ductile-Fragile Transition: A Novel Comparison Between Fracture Mechanics of Materials and Framed Structures

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in collaboration with

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- Structural Collapse and Fracture Mechanics
- Ductile-Fragile Transition of Materials
- Analogies with Progressive Collapse of 2D Frames
- Implications for Structural Design and Engineering
- Conclusion and Q&A

Structural Collapse and Fracture Mechanics

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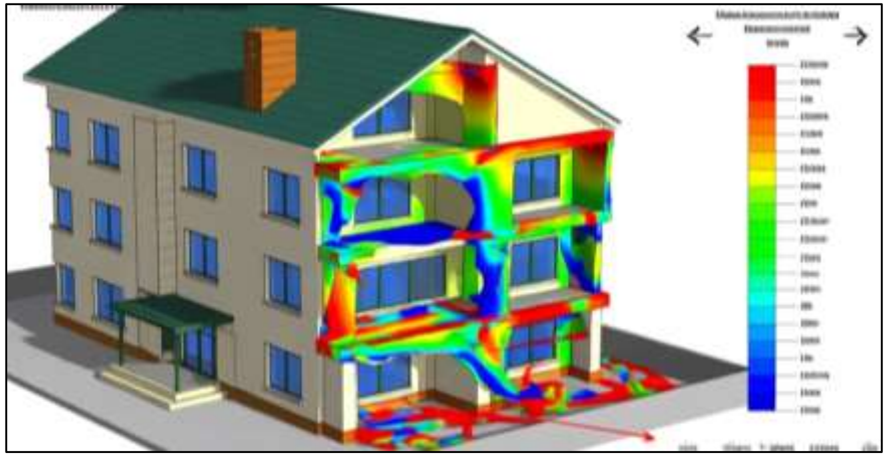
Structural Collapse and Fracture Mechanics

Modern engineering design rules relies on two design limits: the serviceability limit state (SLS) and the ultimate limit state (ULS).



However, real-world failures highlight the need to understand material behavior under extreme conditions, especially with defects or damage.

Fracture mechanics, pioneered by A.A. Griffith in 1920, provides the framework for understanding how cracks initiate and propagate, explaining why structures can fail at stress levels far below their theoretical strength.

Structural Collapse and Fracture Mechanics

A comprehensive analysis must consider how individual elements behave before scaling to the full system. Key factors include:

Material Behavior

Intrinsic properties like ductility, brittleness, and toughness that determine failure modes.

Geometric Effects

Shape, dimensions, and stress distribution that influence crack formation, especially at points of stress concentration.

Load Conditions

External factors like cyclic loading, impacts, and temperature variations that can accelerate deterioration.

Hierarchical Organization

which affects how forces redistribute after initial damage.

Ductile Fragile Transition of Materials

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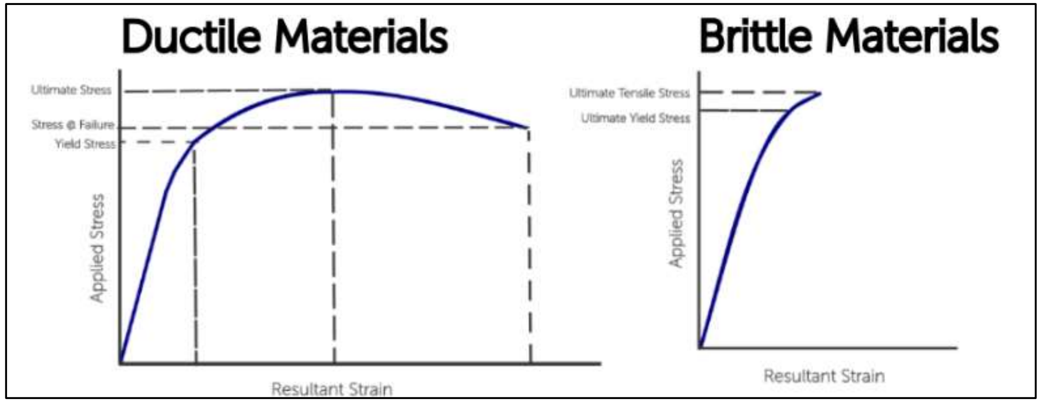
Ductile-Fragile Transition of Materials

The shift from a gradual, energy-absorbing failure (ductile) to a sudden, catastrophic rupture (brittle) is a fundamental concept in fracture mechanics.

Ductile Materials

Like structural steel, they undergo significant plastic deformation before failure, absorbing substantial energy. This makes them resilient to sudden failure.



Brittle Materials

Like concrete and glass, they have limited plastic deformation. Pre-existing flaws act as stress concentrators, leading to abrupt failure once a critical stress is reached.

The transition from ductile to brittle collapse depends on a dimensional effect, particularly the crack length 'a'. A characteristic length 'a_0' can be defined.

- For $a < a_0$, collapse is ductile.
- For $a > a_0$, brittle collapse precedes plastic collapse.

$$a_0 = \frac{K_I^2}{\pi \sigma_P^2}$$

Where K_I is the stress intensification factor and σ_P is the ultimate tensile strength.

$$\frac{P_{\max} L}{\sigma_P t H^2} = \left(1 - \frac{a}{H}\right)^2$$

Beam Relation which links the ultimate plastic load (P_{max}) to the beam's geometry (L, H, t) and crack width (a).

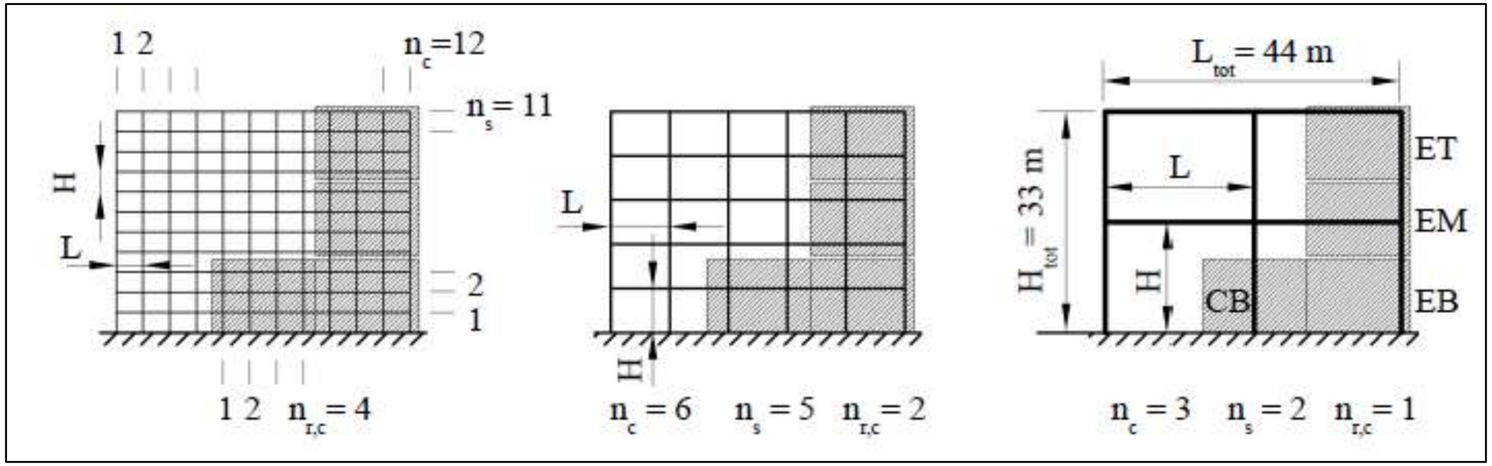
Analogies with Progressive Collapse of 2D Frames

Analogies with Progressive Collapse of 2D Frames

The study analyzes 2D reinforced concrete frames of varying structural hierarchies: 2x2, 5x5, and 11x11. All frames have the same overall size but differ in the number and scale of their elements. The hierarchical level is defined as 1/n.

- 2x2 Frame: Highly hierarchical with fewer, larger elements.
- 5x5 & 11x11 Frames: More heterogeneous with a greater number of smaller elements.

The frames are subjected to the sudden removal of beams and columns within a predefined damage area (CB damage scheme).



Analogies with Progressive Collapse of 2D Frames

Intact Structures

	2x2	5x5	11x11
P_{max} [kN]	433125	173250	78750
L [m]	22	8.8	4
σ_p [kN/m^2]	35000	35000	35000
t [m]	1	1	1
H [m]	16.5	6.6	3
a [m]	0	0	0

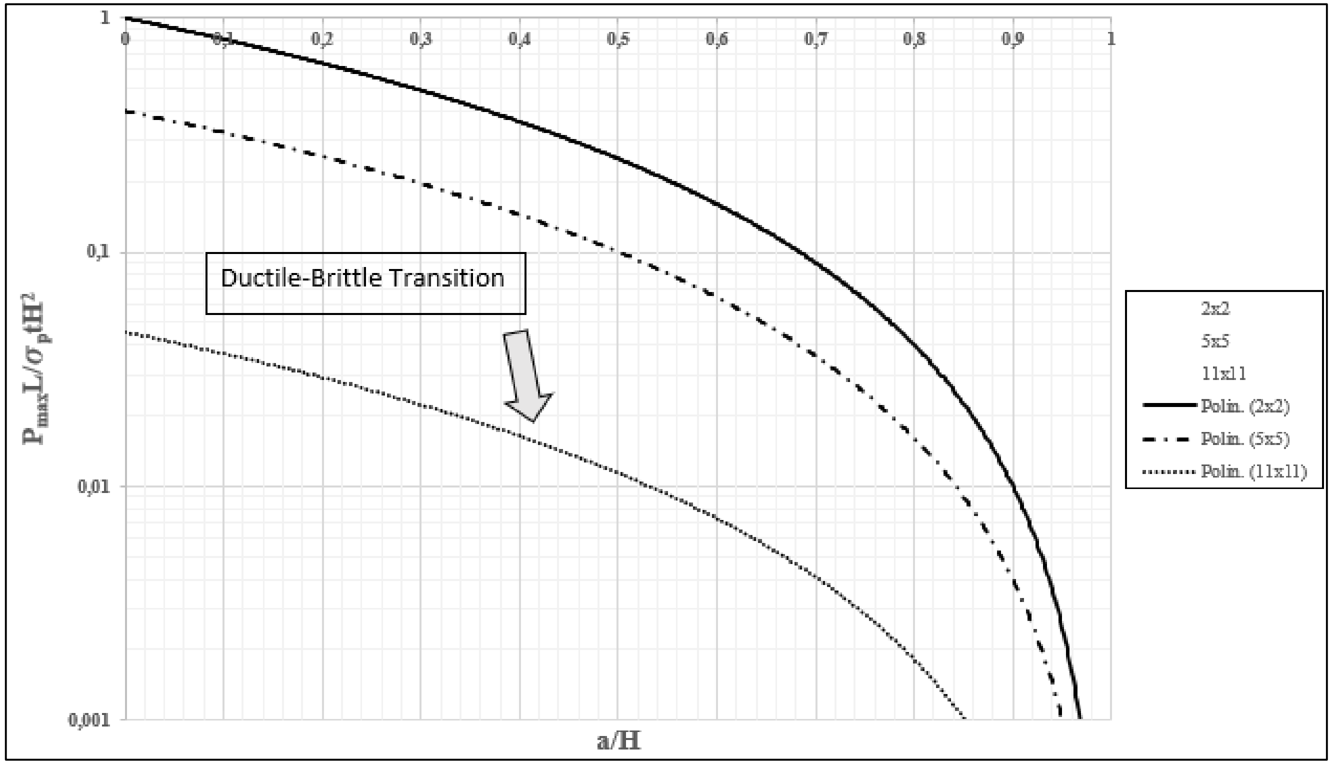
Damaged Structures (CB Scheme)

	2x2	5x5	11x11
P_{max} [kN]	54141	15593	3986
L[m]	22	8.8	4
σ_p [kN/m^2]	35000	35000	35000
t [m]	1	1	1
H [m]	16.5	6.6	3
a [m]	8.3	2.6	1.1

Analogies with Progressive Collapse of 2D Frames

The graph shows the variation of the dimensionless ultimate plastic load with respect to the damage zone width 'a' for different hierarchies. For a given damage size, the more hierarchical structure (2x2) sustains a greater load than the less hierarchical ones (5x5, 11x11).

- The 2x2 frame has the highest ultimate load capacity when intact due to better load redistribution.
- Hierarchical structures show a sharper decline in strength once damage exceeds a critical threshold (approx. half the inter-story height).
- Beyond this threshold, the robust 2x2 frame becomes as vulnerable as the less organized 5x5 and 11x11 frames.

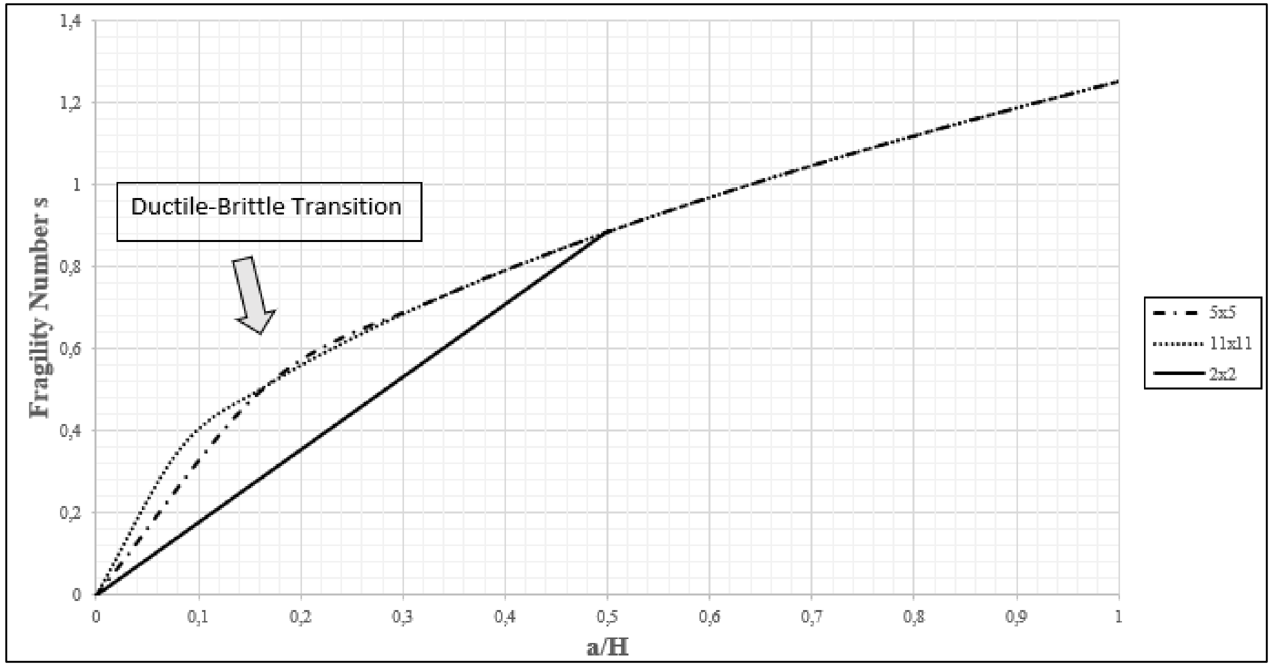


- **This behavior mirrors material fracture, where a crack becomes critical and leads to sudden failure after reaching a certain length.**

Analogies with Progressive Collapse of 2D Frames

A 'fragility number' is used to quantify a structure's susceptibility to brittle collapse.

- High hierarchy enhances initial robustness but creates a more pronounced transition to brittle failure.
- The 11x11 frame shows that too many small elements can reduce load redistribution capacity, making the structure more fragile even with minor damage.
- There is a threshold beyond which reducing hierarchy (increasing 'n') leads to a disproportionate increase in fragility.



Implications for Structural Design and Engineering

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The findings have significant implications for preventing progressive collapse. Designers must carefully balance the trade-off between structural hierarchy and redundancy.

- Optimize Resilience: Don't just focus on initial strength; consider how the structure will behave once damaged.
- Apply Fracture Mechanics: The principles governing material cracks can be used to predict how localized damage affects entire structures.
- Develop New Methodologies: Integrate these insights to create predictive models that mitigate the risks of brittle, catastrophic failure.

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Thanks for your attention !

Questions?