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Robust design of steel framed buildings against extreme loading

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Introduction

- Robust frames subjected to earthquakes and other hazards such as explosions require relatively weak beams, but strong connections and columns
- For earthquake design - dissipative collapse mechanisms
- Design due to explosion hazards - avoid progressive collapse
  - bracing systems
  - or, more commonly, alternative load paths (catenary action of the floor members)
- Objective for robustness
  - ensure failures are ductile
  - avoid connection failures

Building illustrating the significant connection rotations developed following bomb attack

Resulting connection failure

Introduction

- Also for steel constructions, a robust structural design cannot be easily achieved, since there are several factors that can cause a brittle behavior of some components (e.g. the beam-to-column connections):
  - strain hardening
  - the routine supply of over strength steel
  - high rates of strain, ….
- These factors are investigated in this paper, providing useful issues that can guide to a correct design of robust steel frames to avoid premature collapse due to extreme loading.

Introduction

- A common feature of extreme loads is that they are intense and of short duration. This applies to seismic, impact and blast loads
- It is the ability to absorb energy through ductility that is the primary factor in survivability.
- This concept was recognized by the automotive industry with the transfer to the “crumple design” method:
  - Maximise energy absorption through plastic deformation
  - Provide strong connections between relatively weak components to prevent brittle failures

Introduction

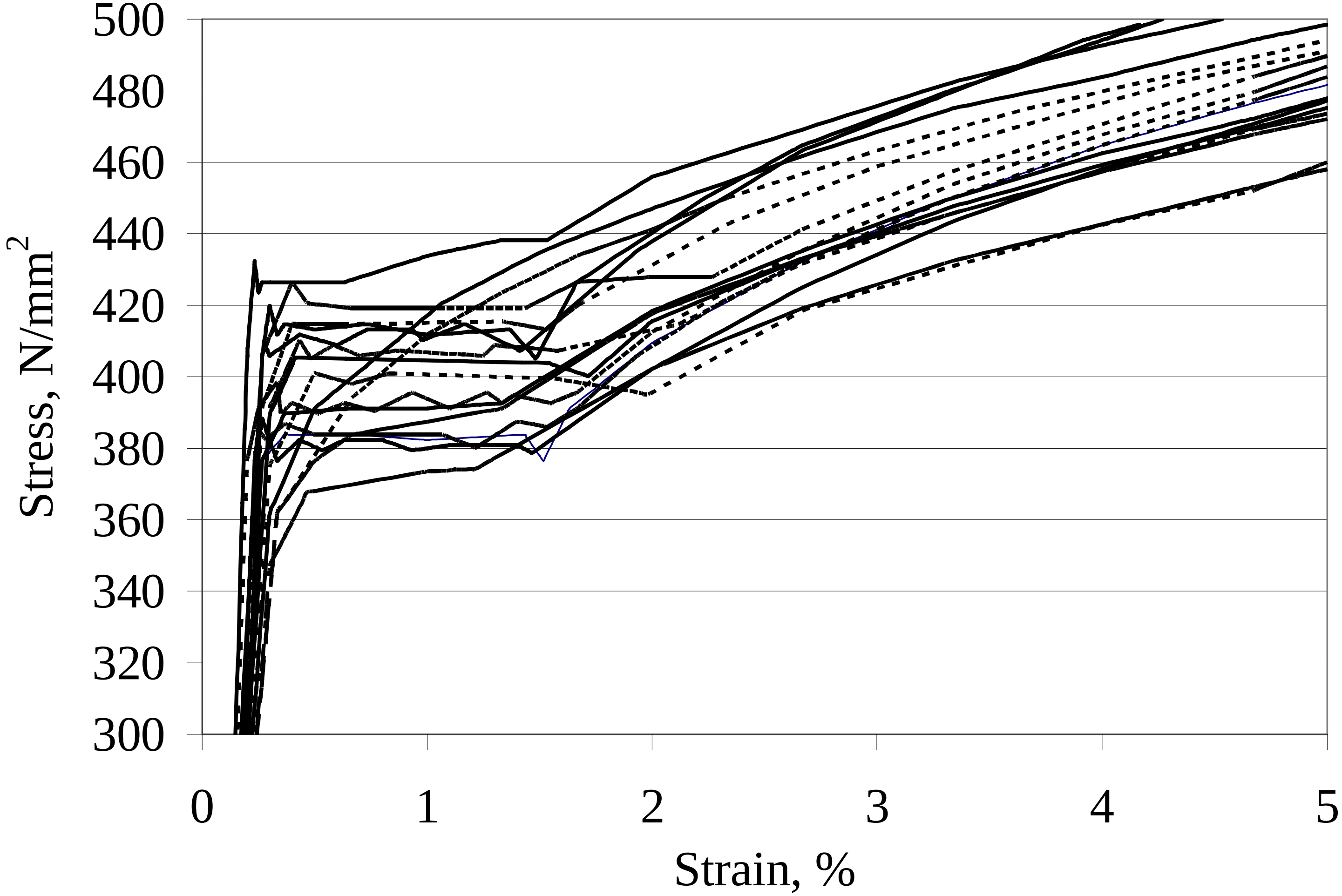
- Unfortunately, extreme loads do not fit easily within the ULS design approach because the implication of the ULS load being exceeded is not considered.
- Furthermore, ULS design, based on lower-bound strength calculations, has been shown to be capable of producing a mismatch between the strength of beams and their connections (Byfield, 2004).

Flexural strength can typically exceed double the ULS design strength because of:

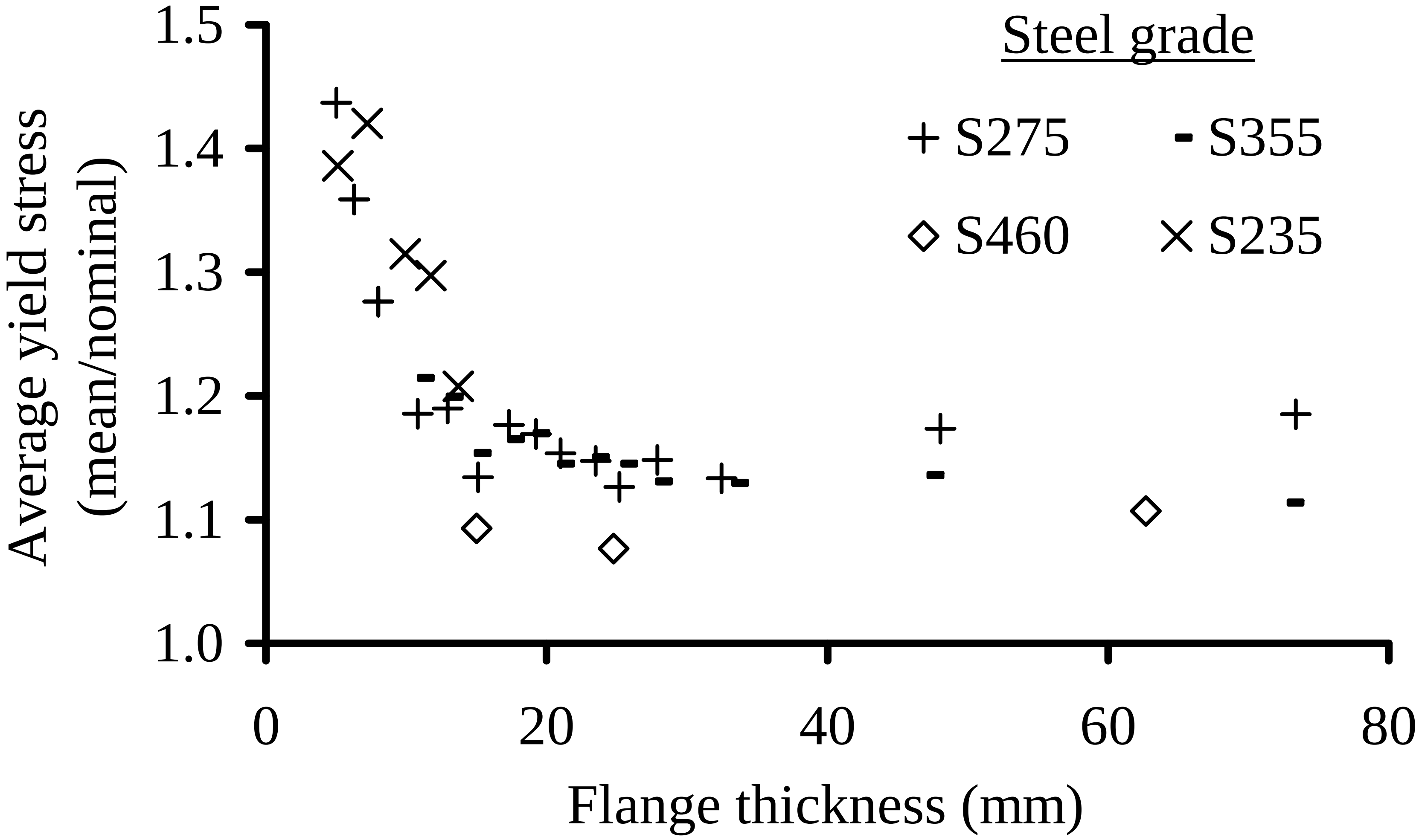
•Over strength steel

•Strain Hardening

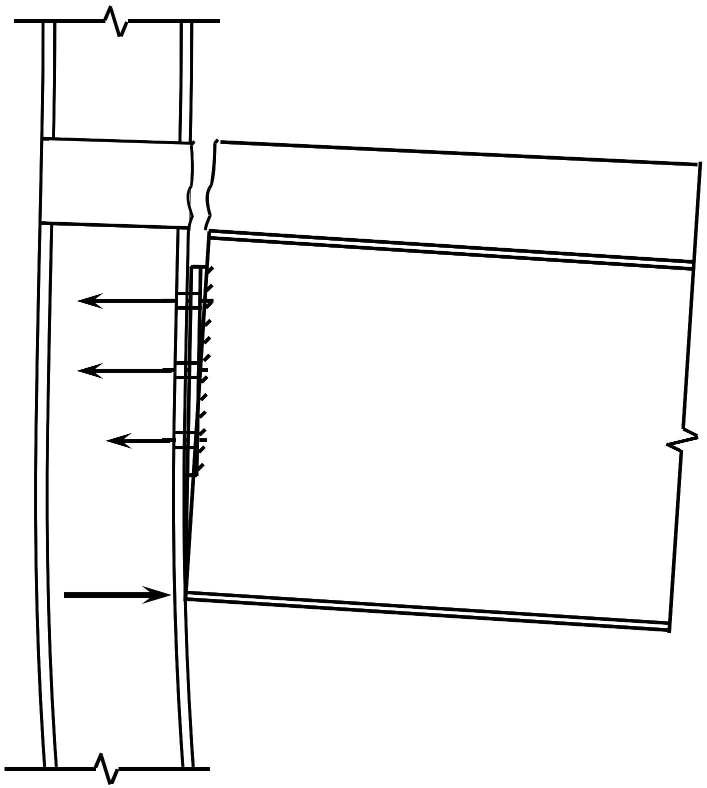
•Moment resisting nominally pinned connections



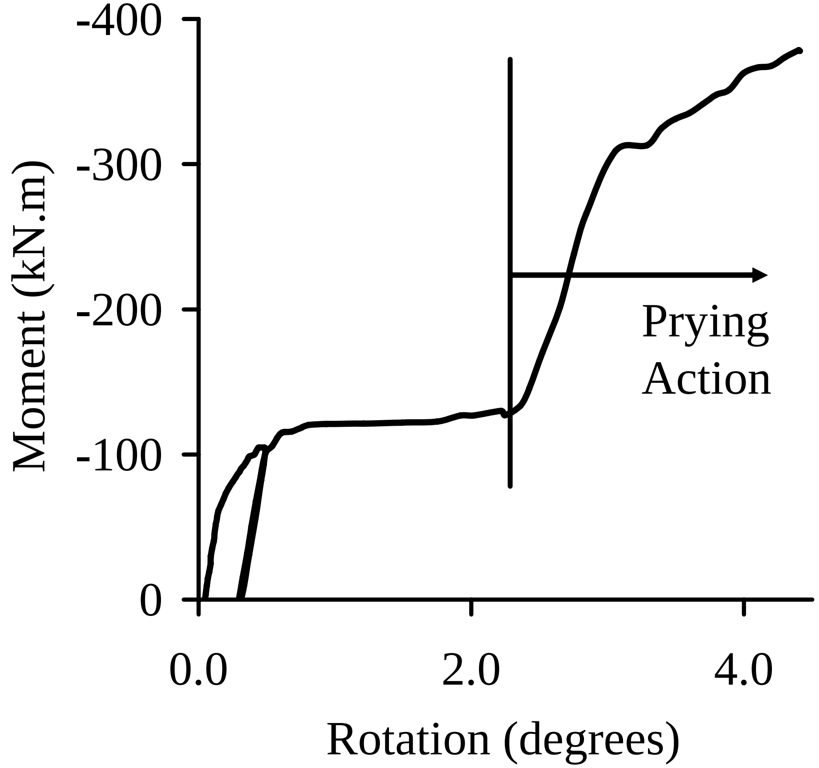
Strain Hardening: Experimental stress strain behaviour of S355 steel



Over-strength steel: results from over 7000 measurements of yield stress

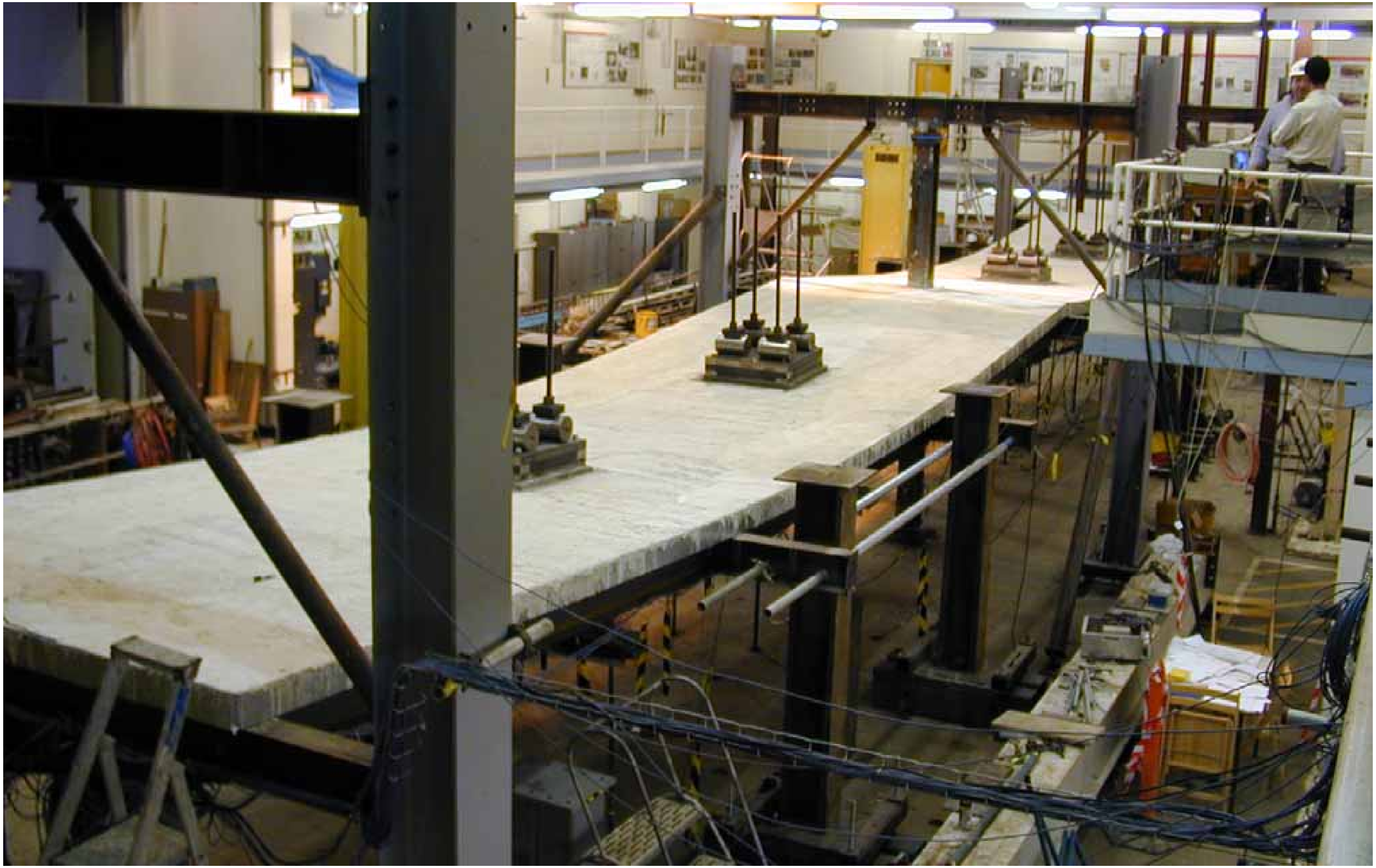


Prying action response to rotation



Moment rotation behaviour

Illustration of ductility problems associated with partial depth "nominally pinned" flexible end-plate connections



Combined effects of low-ductility connections, over strength steel and strain hardening doubled the flexural ULS strength

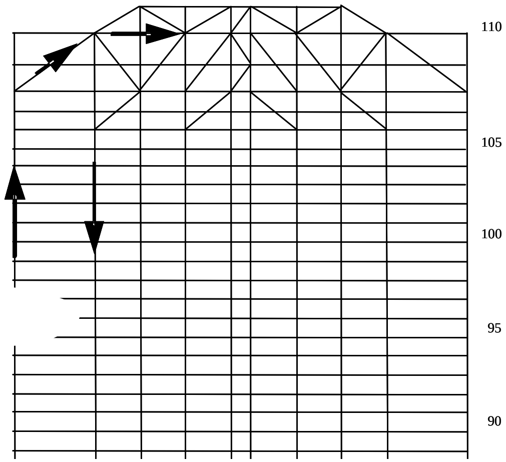
Introduction

- Robust design of structures may be achieved by means of high redundancy, i.e. incorporating moment beam-to-column connections having large over strength or by using other dissipative sources in the structure (bracings, dampers and so on).
- A useful alternative, when the structures are designed for gravity loading only and simple connections are of concern, may be based on the employment of very ductile pinned connections, that could favour the development of catenary resistant mechanisms at large deformation stages.
- The former approach is typically adopted in earthquake prone countries, while the latter in simply supported steelwork frames subjected to exceptional actions.

Redundancy as a basis for robust steel frames

- All around the world, steel structures are extensively used for high-rise buildings and large span structures.
- Because of their location many structures could be subjected to exceptional situations, for instance due to terrorist attacks
- Different strategies can be adopted to avoid the progressive collapse of a structure (De Matteis *et al*, 2006):
  - Event control, which aims at avoiding and/or protecting the building against an accident that might lead to the progressive collapse;
  - Indirect design, which aims at providing adequate resistance against the progressive collapse through a minimum level of strength and ductility of the applied structural components;
  - Direct design, which considers explicitly the strength of the structure for progressive collapse and its ability to absorb damages
    - Key element strategy
    - Alternative load paths strategy

Redundancy as a basis for robust steel frames

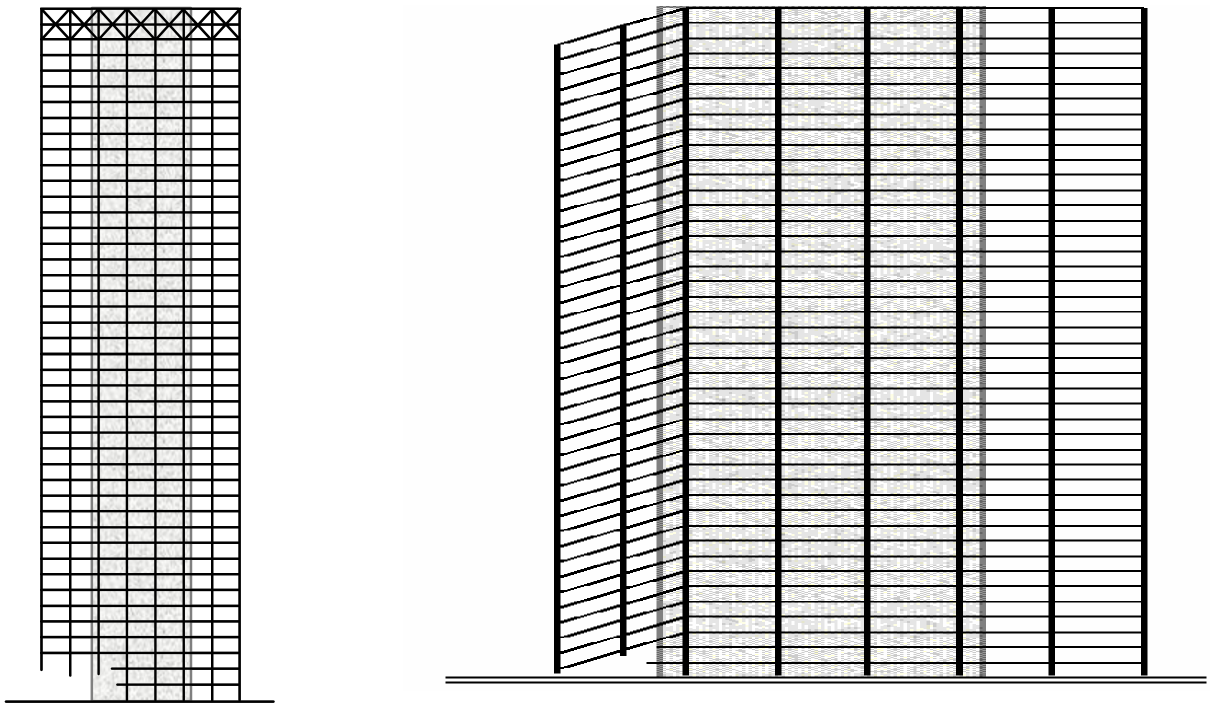


Section through WTC1 showing load path through hat-truss

It can be speculated that these alternative load paths were partly responsible for preventing immediate collapses following the aircraft impacts.

Redundancy as a basis for robust steel frames

- Redundancy can be simply defined as the ratio between the collapse load of the structure in the original state and the collapse load of the structure where structural elements are damaged.



Different degrees of redundancy

The capacity design approach

- When building structures are subjected to extreme loading conditions, such as earthquakes or blast, in order to guarantee the structural integrity it is necessary to provide sufficient robustness to elements and their connections. Recently, new approaches aiming at designing more robust structures were introduced in the codes. One of these new approaches is termed capacity design.
- According to the capacity design approach, in case of seismic design, the elements of the structural system are chosen and suitably designed and detailed for energy dissipation under severe deformations while all other structural elements are provided with sufficient over strength so that the chosen means of energy dissipation can be maintained (EN1998-1).

The capacity design approach

- A robust structural system cannot be easily achieved, since there are several factors that may adversely affect it, including:
  - strain hardening
  - the routine supply of over strength steel
  - high strain rates
- According to the capacity design method, the non-dissipative members and the connections of the dissipative members to the rest of the structure should have sufficient overstrength

$$\mathrm{R_d} \geq 1{,}1\gamma_{\mathrm{ov}} R_{fy}$$

- In order to avoid the development of plastic hinges in the non dissipative members (i.e. columns), EN1998-1 increases the forces and moments due to the design seismic action by a multiplier equal to $1{,}1\gamma_{\mathrm{ov}}\Omega$

The capacity design approach

- A limitation of this method is that even the design of the non-dissipative members is done using such amplified forces, and they provide no guarantee that they will behave entirely in the elastic range.
- Moreover, it should also be recognized that although the application of capacity design approach improves the robustness of the structure, the additional costs may lead to an uneconomical structural solution.
- Therefore, the proper design needs to be based on more advanced static or dynamic inelastic analysis. For these reasons, this methodology requires more studies to be done.

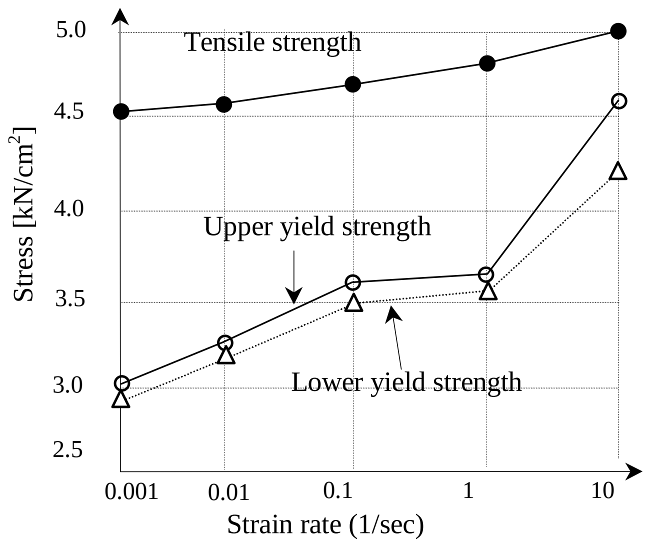
Factors affecting the local ductility of steel frames

- The energy exerted on a building frame during extreme loading conditions is partly stored in the shape of kinetic and elastic strain energy and partly dissipated in the shape of plastic deformation in the critical zones.
- Increasing the stored energy leads to higher forces and increases the demand for higher resistance, while increasing the plastic strain energy increases the demand for higher ductility.
- There are some factors which may adversely affect the local ductility
  - strain hardening
  - the routine supply of over strength steel
  - the hogging moments at the supports due to over-strength "nominally pinned" connections
  - low cycle fatigue
  - high strain rates
  - temperature

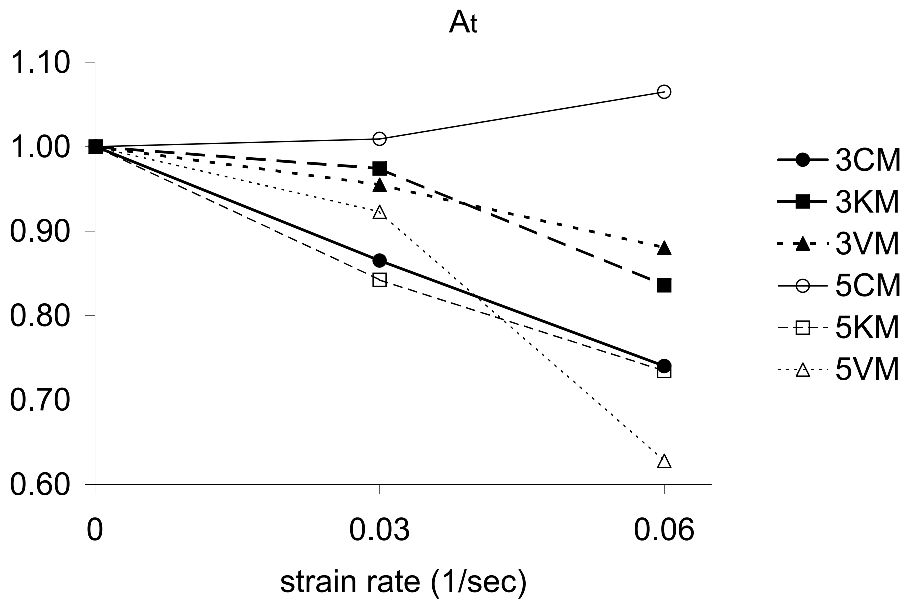
Factors affecting the local ductility of steel frames

- Structural connections designed to resist seismic loads are likely to have a good ability to resist blast loading.
- High strain rates may cause a significant reduction in both tensile strength and ductility.
- Importantly, strain rate weakening combined with strain rate hardening for plate material can be expected to reduce the ductility of joints and lead to brittle failure mechanisms for many popular structural details used in non-seismic regions.
- In case of blast loading, which is typically a monotonic loading, the main cause of poor behaviour is due to the severe reduction of the ductility, up to 30%.

Factors affecting the local ductility of steel frames



Yield stress and tensile strength vs. strain rate



Ductility (elongation at fracture) vs. strain rate for monotonically loaded welded specimens

Conclusions

- Buildings designed to resist seismic loads have a good ability to resist blast loading when compared with buildings designed to resist only gravity and wind loads. This is because the strategies employed to resist seismic actions generally aim to provide ductility and redundancy.
- The design of buildings to resist localised damage from blast without collapse is a relatively new area of structural engineering, whereas design to resist seismic actions is a mature discipline.
- This paper discusses the application of a seismic design method know as capacity design for design to resist blast
- The capacity design method is shown to have potential for improving the ductility of frames and reducing the likelihood of connection failure.
- It is not possible to transfer the method directly to blast design, because factors such as rate of loading and the resulting strain rate effects differ considerably