FRP composites in bridge design

Bridge Owners' Forum 29 Jan 2013

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FRP Composites in bridge design

Introduction

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FRP Composites in bridge design

Agenda

What is NGCC?

What are FRP Composites?

Why use them in bridges?

What have we learned so far?

What challenges remain?

Recent developments in design guidance

Future opportunities

FRP Composites in bridge design

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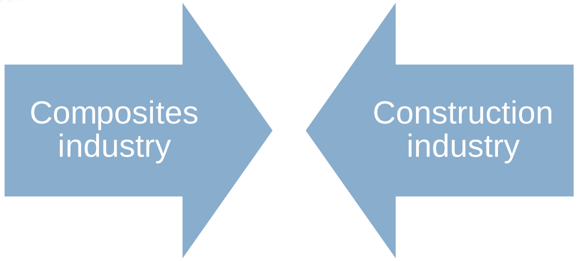
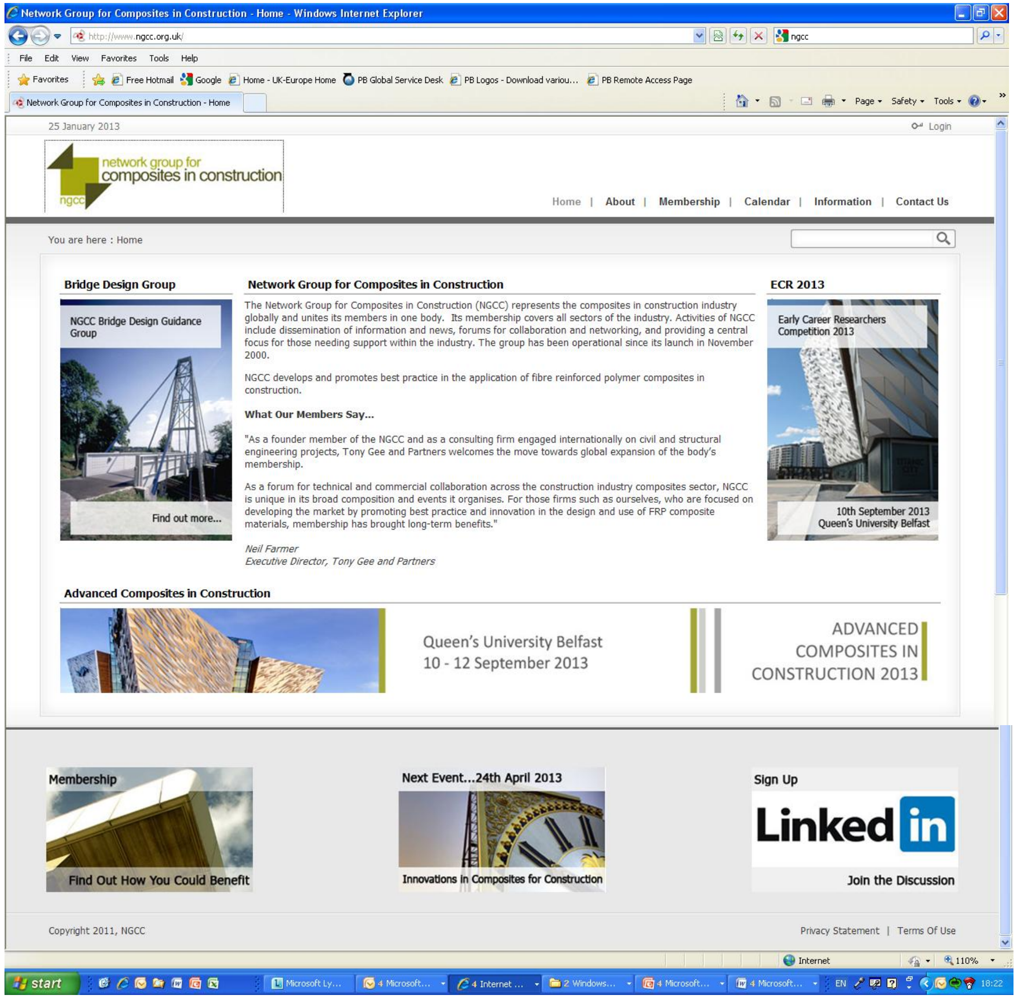


- Encourages effective use of FRP
- Partnering + collaboration
- Raise profile
- Provide information
- Training and events



FRP Composites in bridge design

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Our members include:

clients, designers, architects, contractors, suppliers, manufacturers, academics…

Benefits:

- Networking with professionals across industry and academia
- Collaboration and research opportunities
- Technical information in website members area
- Exhibition opportunities
- Special rates at events

Image courtesy of Steni UK Limited

FRP Composites in bridge design

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NGCC

- provides representation on the European working group to develop eurocodes for FRP composites
- Has set up a bridge design group developing design guidance
- Has set up subgroups to coordinate FRP research and development and training

Image courtesy of Steni UK Limited

FRP Composites in bridge design

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FRP Composites in bridge design

FRP Composites

Benefits

- Non-corroding
- Do not need painting
- Light weight
- Strong
- Able to resist harsh environments
- Can be non-conductive and non-magnetic

Image courtesy of Parsons Brinckerhoff

FRP Composites

Fibres

- Glass
- Carbon (standard and high modulus)
- Aramid
- Basalt

Resin matrix

- Polyesters
- Vinyl esters
- Epoxies
- Phenolics
- Thermoplastics (eg polyamides)

Additives

FRP Composites in bridge design

FRP Composites

Properties

TABLE 3 - TYPICAL UD LAMINATE PROPERTIES

	E-GLASS	ARAMID (Kevlar 49)	HIGH STRENGTH CARBON	HIGH MODULUS CARBON	STEEL (Grade S275)	CONCRETE
Tensile Strength (MPa)	650	900	1000-1900	800-1400	275 Yield 430 Ultimate	2-5
Compressive Strength (MPa)	550	250	~1000	~600	275 Yield 430 Ultimate	25-60
Tensile Modulus (GPa)	30	50	100-120	140-240	205	25-36
Tensile Failure Strain (%)	2.3	2.2	1.5-2.2	0.6-1.4	20	0.01
Density (Kg/m3)	1700	1300	1440	1480	7900	2400
Coefficient of Thermal Exp (10^{-6}/iC)	10	-1	0	0	12	7-12

Unidirectional Laminate Fibre Volume Fraction Vf = 40%. Properties in longitudinal direction.

Properties are typical values but are highly dependant on laminate quality, fibre volume fraction, etc...

FRP Composites

Manufacturing processes

- Pultrusion

- Variety of moulding processes
  - Open moulding (hand or spray lamination)
  - Vacuum infusion
  - Resin transfer moulding
  - Vacuum bag or press moulding

FRP Composites in bridge design

FRP Composites

Manufacturing processes

- Pultruded components
  - Prismatic sections
  - Standard profiles (off the shelf)
  - Lower partial factors for design
  - Limited geometries

- Moulded components / structures
  - Unlimited geometric possibilities
  - Optimised fibre layouts
  - Can reduce need for joints
  - Bespoke tooling

FRP Composites in bridge design

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Why use them in bridges?

Non-corroding
No need to paint
Light weight – installation advantages

Cost?
Not always the best solution

Particular situations

- Difficult access
- Corrosive environments
- Need to minimise weight on supporting structure
- Quick installation over existing road / railway

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FRP Bridge Structures

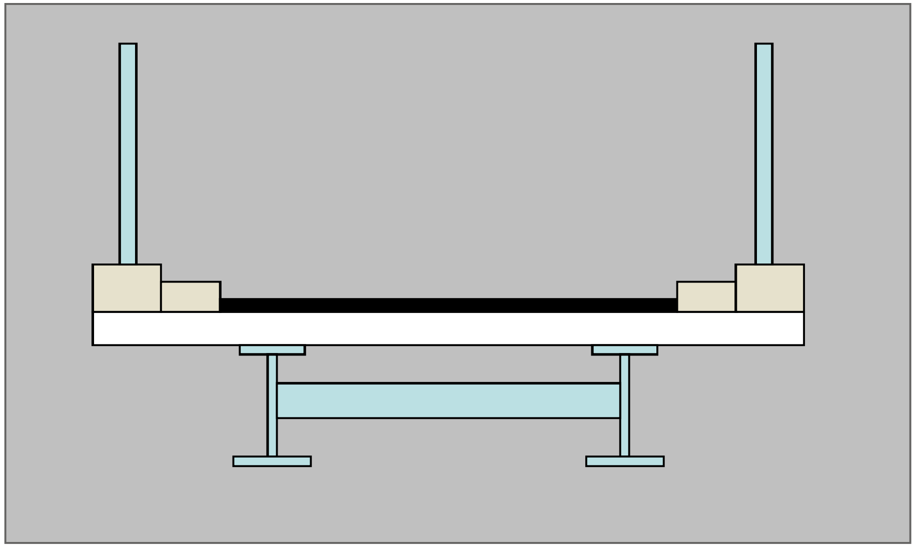
FRP Composites in bridge design

- Overview of FRP bridges

- Case Study: St Austell Footbridge

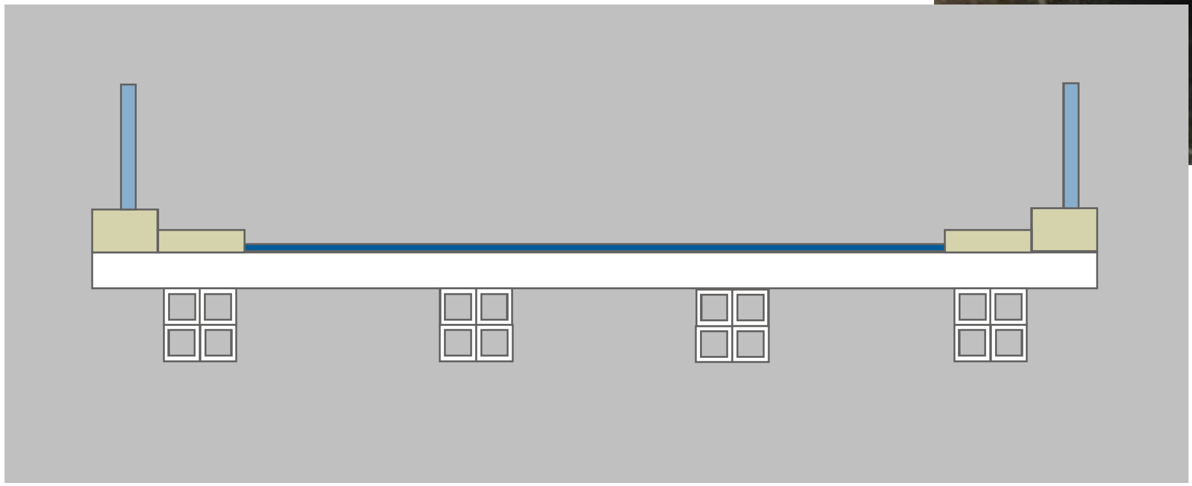
FRP Composites in bridge design

- Motorway overbridges using hybrid system



FRP Composites in bridge design

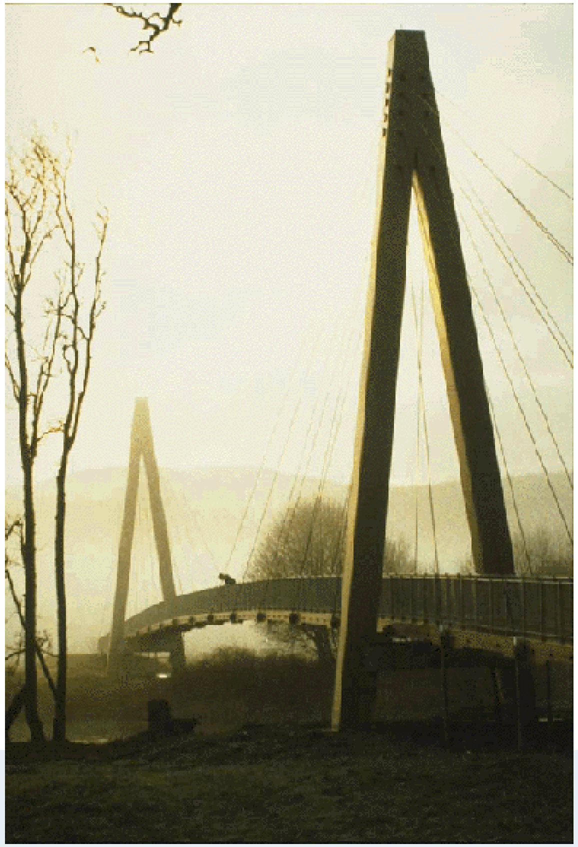
- Short span road bridges



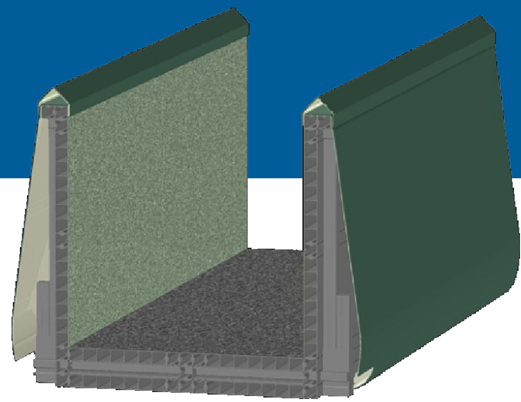
FRP Composites in bridge design

- Lifting bridges

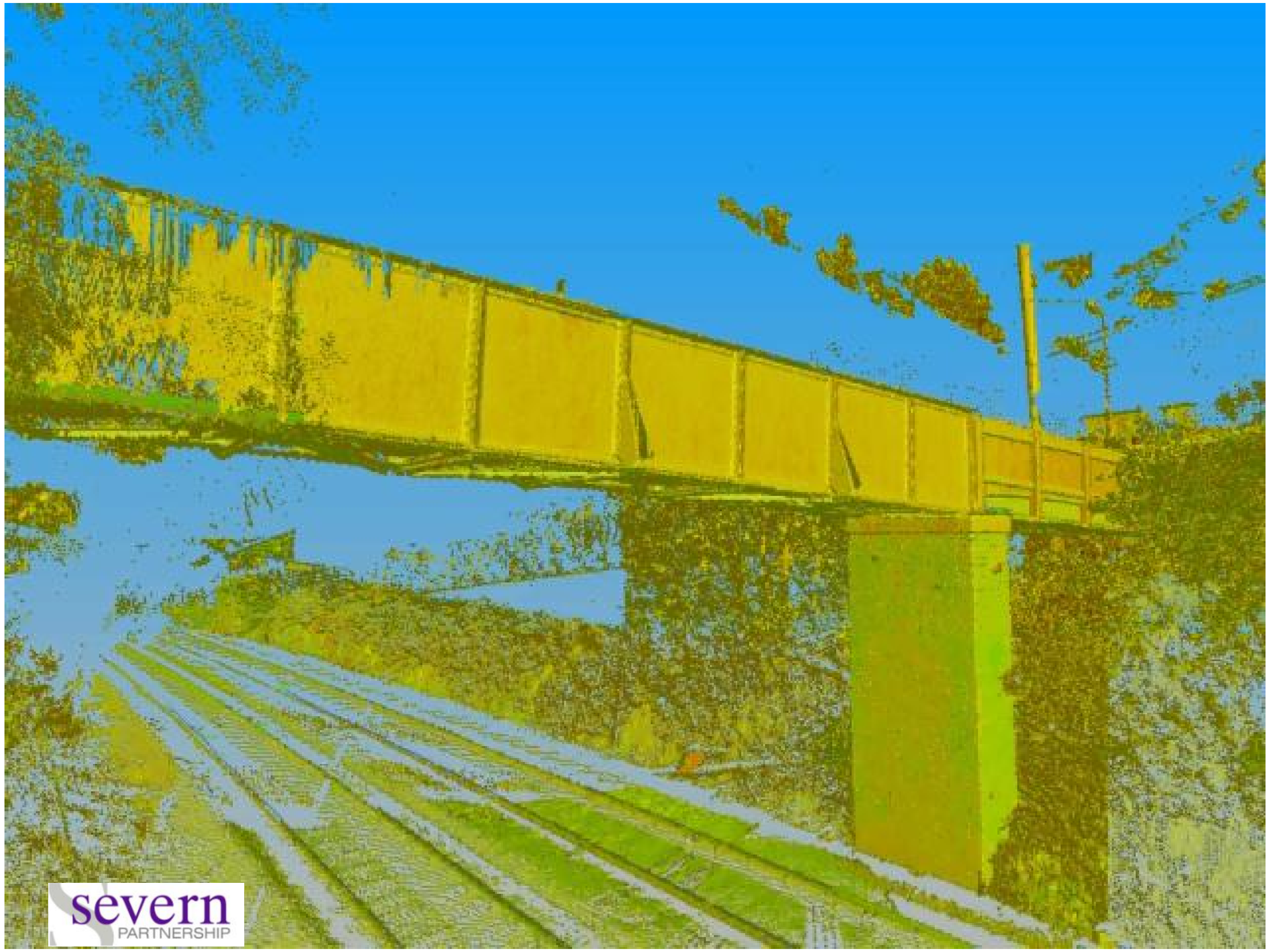
- Footbridges



- Case study: St Austell Footbridge Design



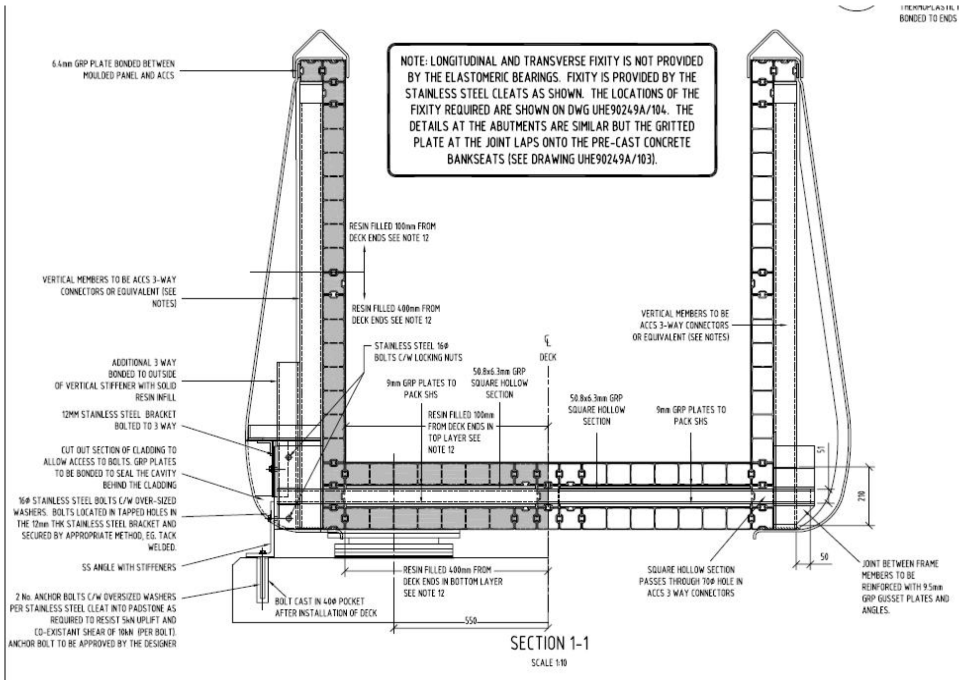
St Austell Footbridge Design

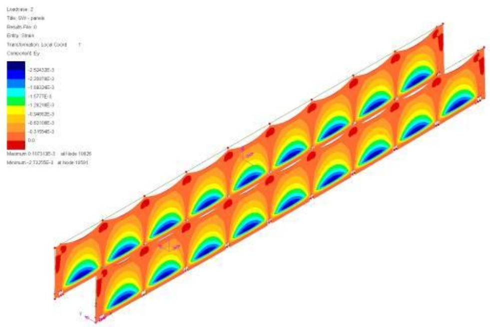


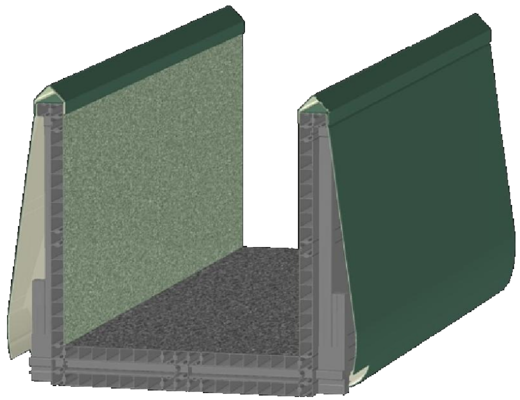
Laser survey of old footbridge

St Austell Footbridge Design

St Austell Footbridge Design

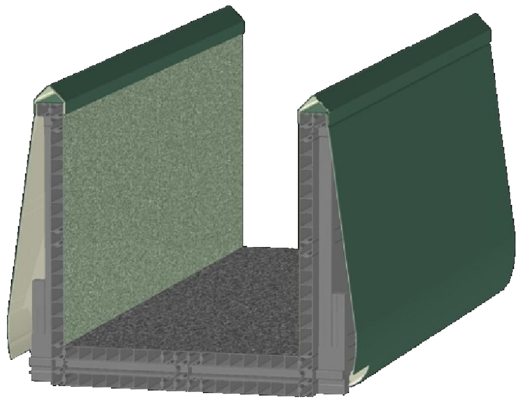






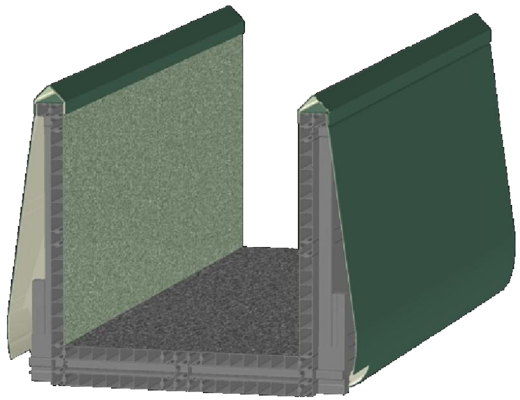
St Austell Footbridge Design

- The first bridge on the UK rail network to be entirely constructed from FRP
- Pultruded main elements
- Moulded exterior skin

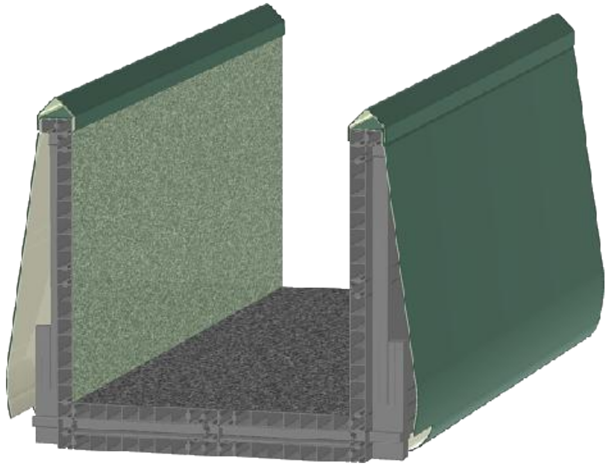


St Austell Footbridge Design

- Pultruded panels bonded and secured with additional mechanical connection
- Design philosophy developed for robustness
- Unexpected joint failure would cause reduction of stiffness, not collapse



St Austell Footbridge Design



Installed October 2007 by Edmund Nuttall

St Austell Footbridge Design

- Bridge is very light (central span is 5 tonnes)
- Potential for vibration caused by train buffeting
- Low mass might result in high accelerations – uncomfortable for pedestrians?
- Magnitude of train buffeting loading?

Vibration research

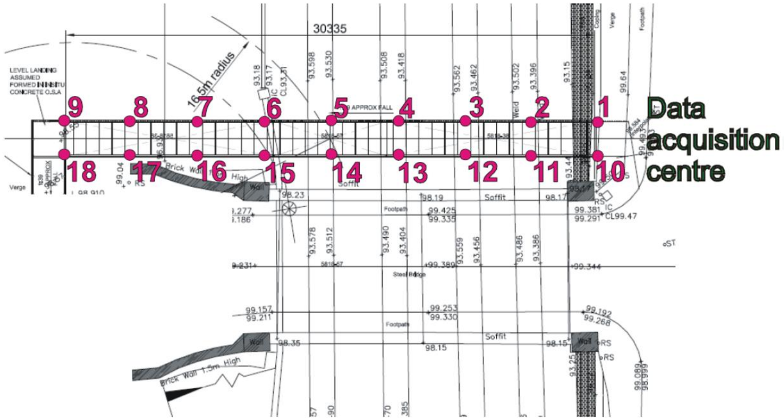
- Goring temporary footbridge
- A very lively structure

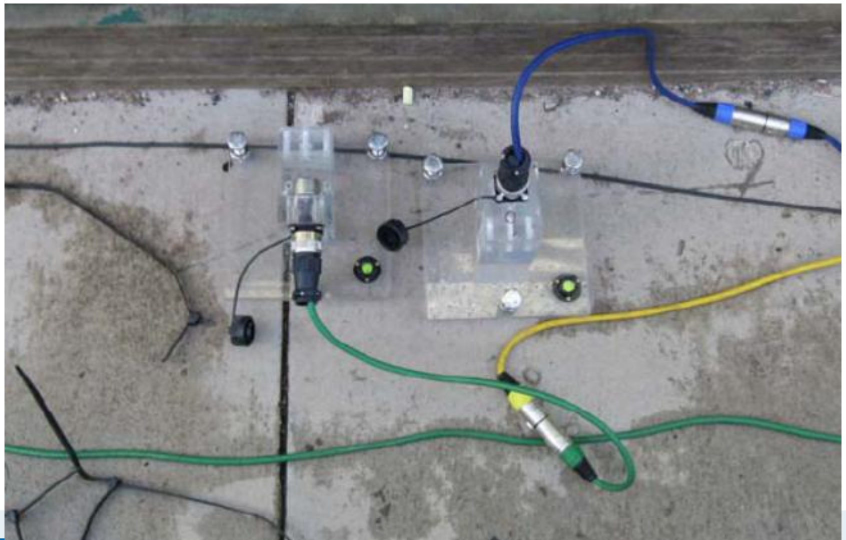
Vibration research

- Dynamic testing carried out with Sheffield University

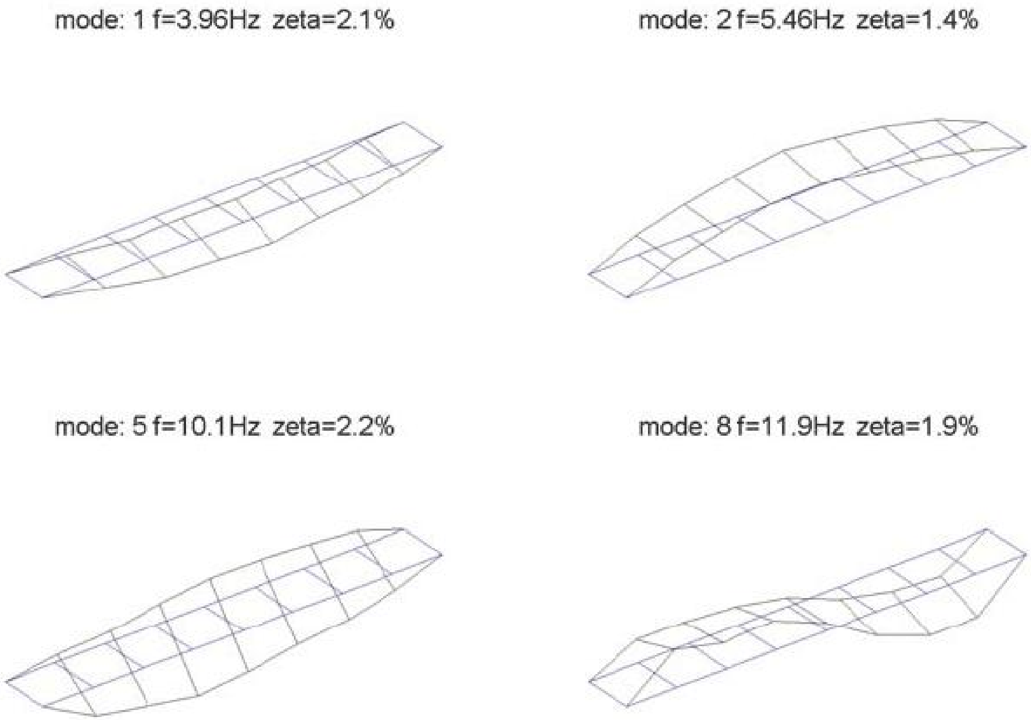
Vibration research

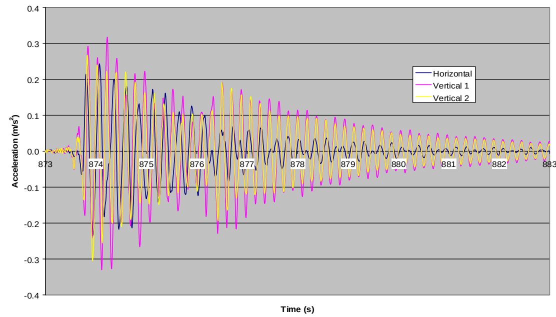
- Accelerometers positioned on structure





Vibration research

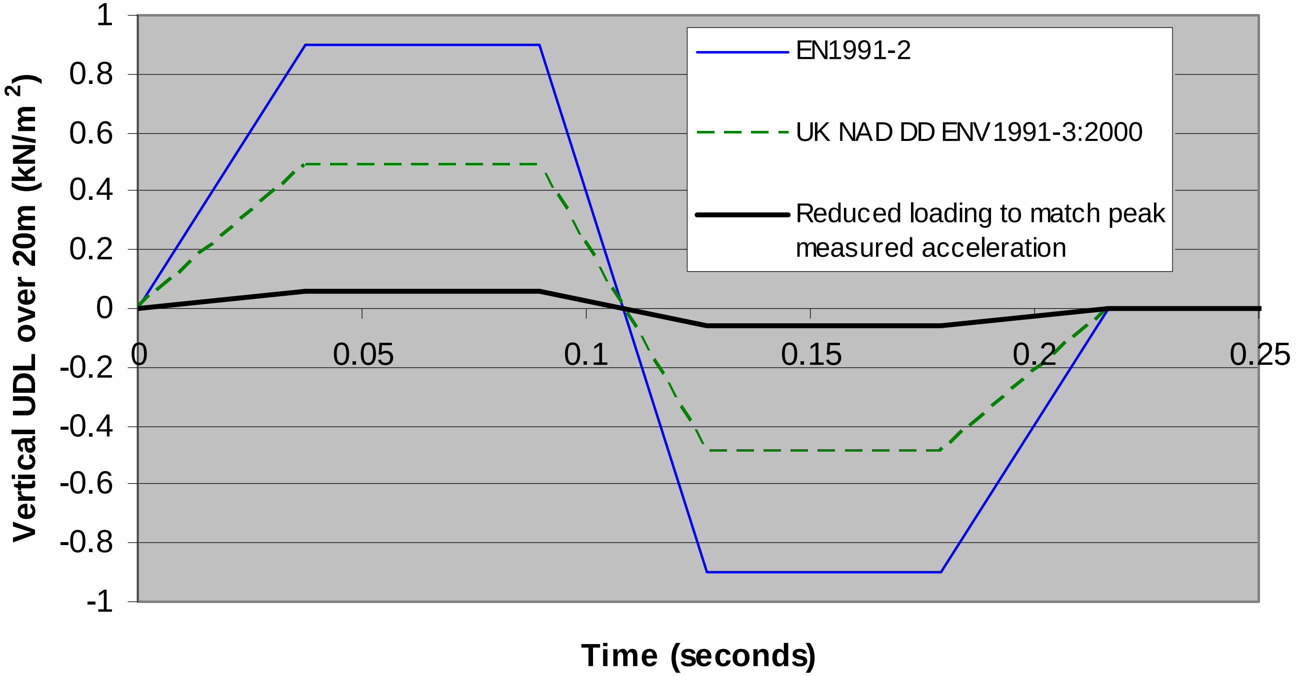




- Determination of modal properties
- Measurement of structure response

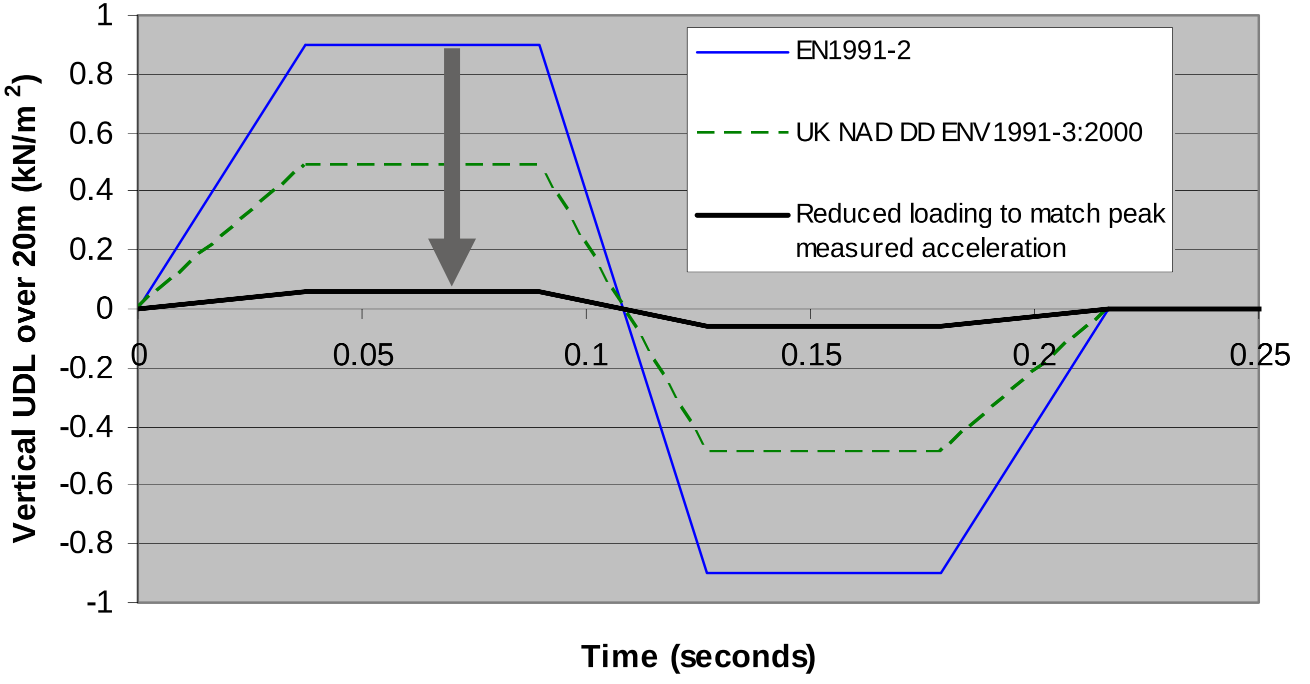
Vibration research

- Comparison of theoretical response with actual response



Vibration research

- Comparison of theoretical response with actual response

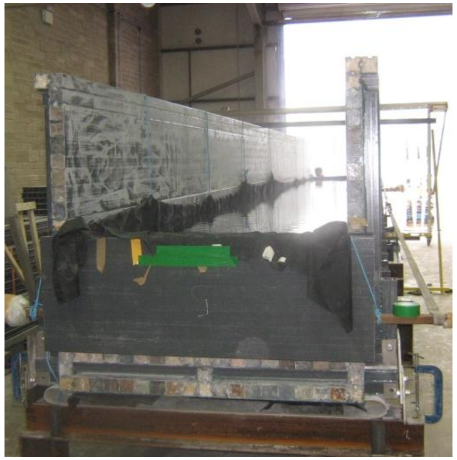


Vibration research

- Derivation of revised loading model based on measurements
- PB-derived loads used to design St Austell Footbridge
- Research provides data to allow lightweight footbridges to be used over railway lines

Testing and monitoring

- Before fabrication
  - Material testing
  - Component testing



- After fabrication
  - Structure load testing

- After installation
  - Dynamic testing & monitoring

Testing and monitoring

- Static load testing

  Water load - uniform

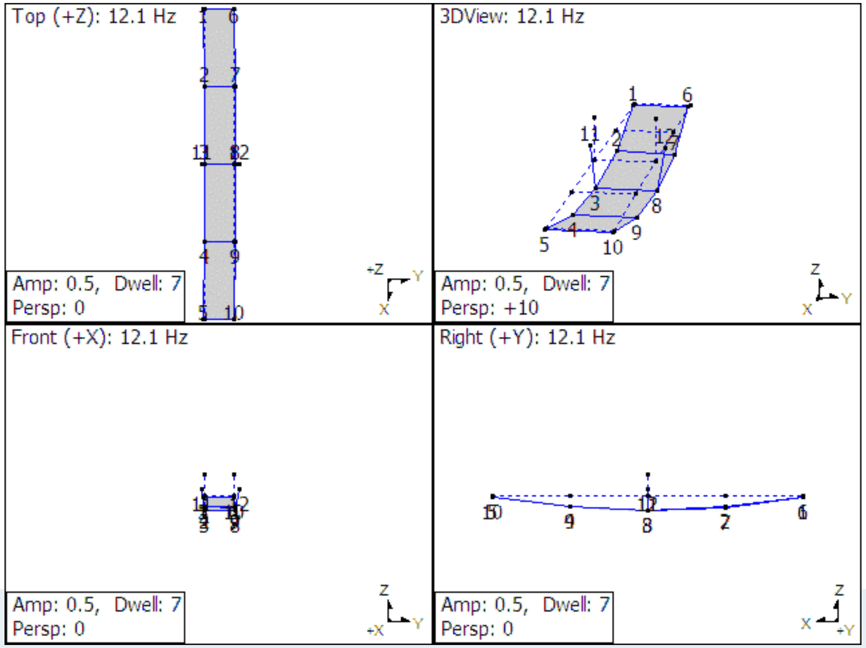
  Linear behaviour

  Small deflections

Testing and monitoring

- Dynamic testing

- Modal properties
- Pedestrian-induced vibrations
- Train buffeting vibrations



Testing and monitoring

- Ongoing monitoring of structure
- Philosophy developed for dynamic monitoring of natural frequencies and modeshapes

FRP Composites in bridge design

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Challenges

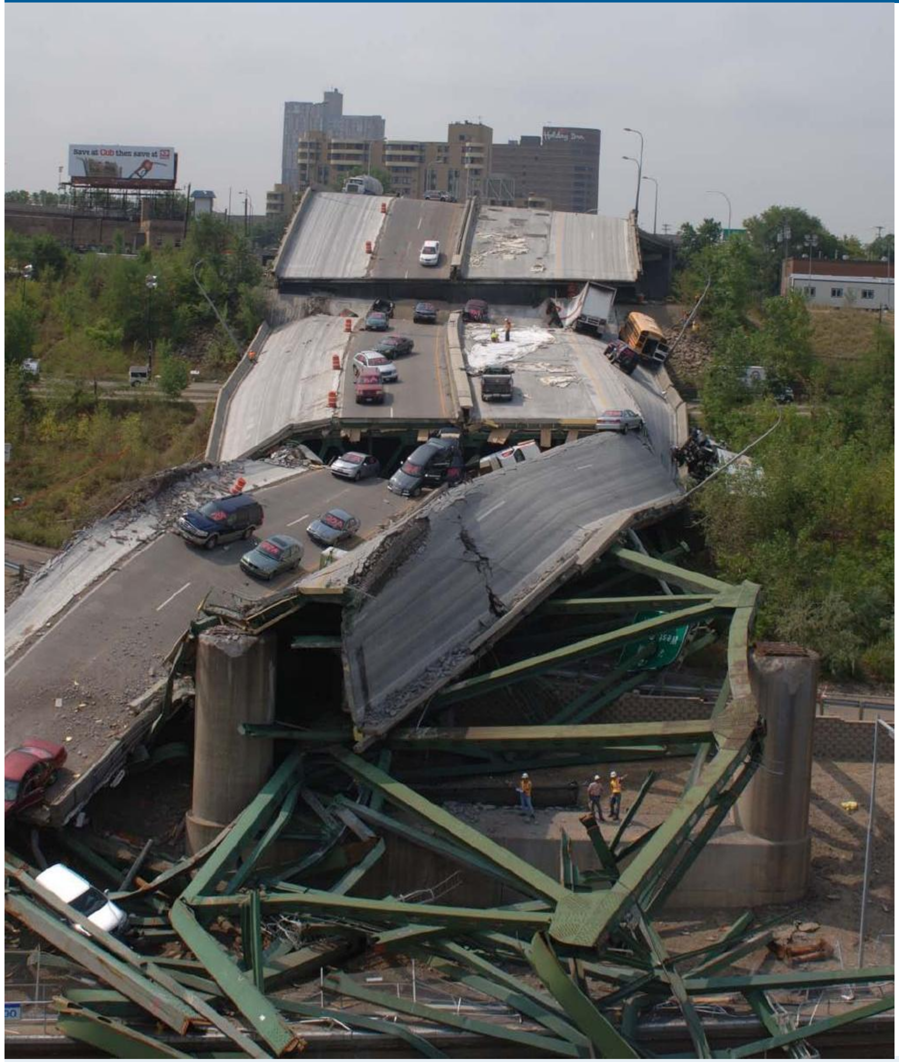
Gaps in codes

Clients unfamiliar with materials?

Costs need to be competitive at construction

Recyclability of materials

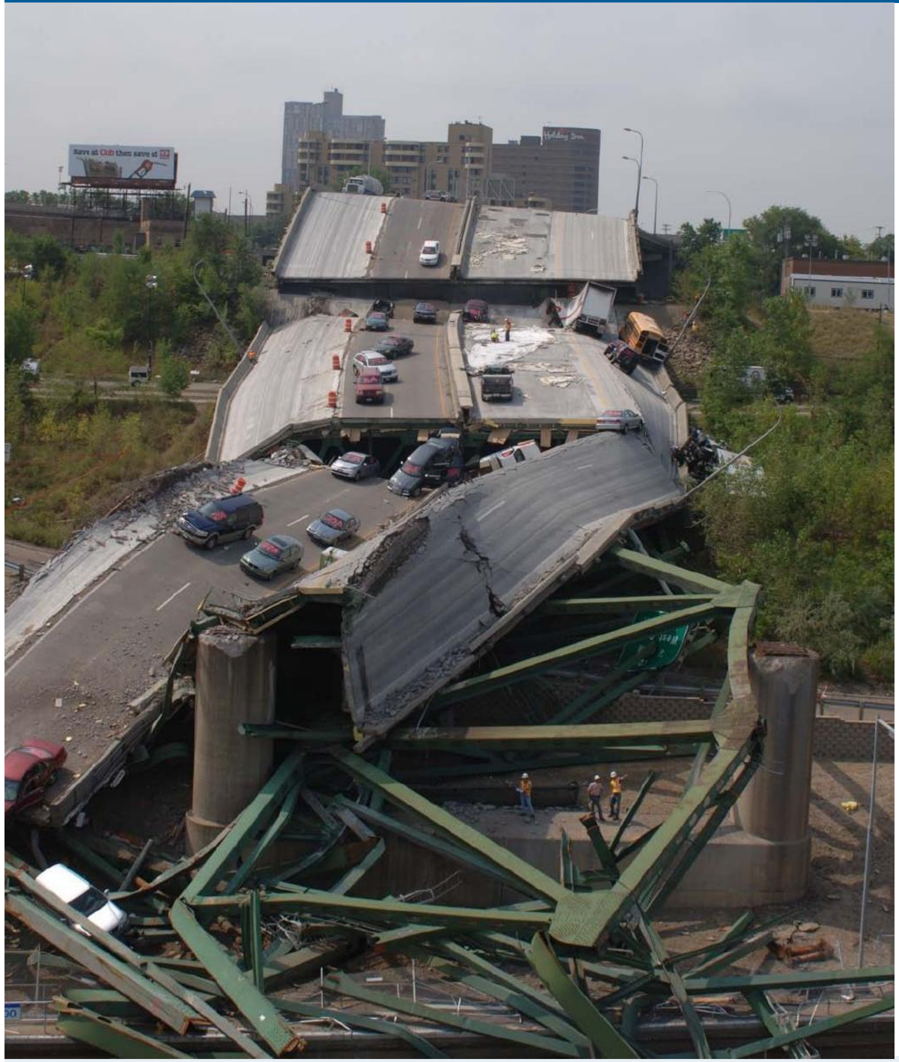
Design issues – eg flexibility, fire, robustness



"Failure is central to engineering … every single calculation that an engineer makes is a failure calculation.

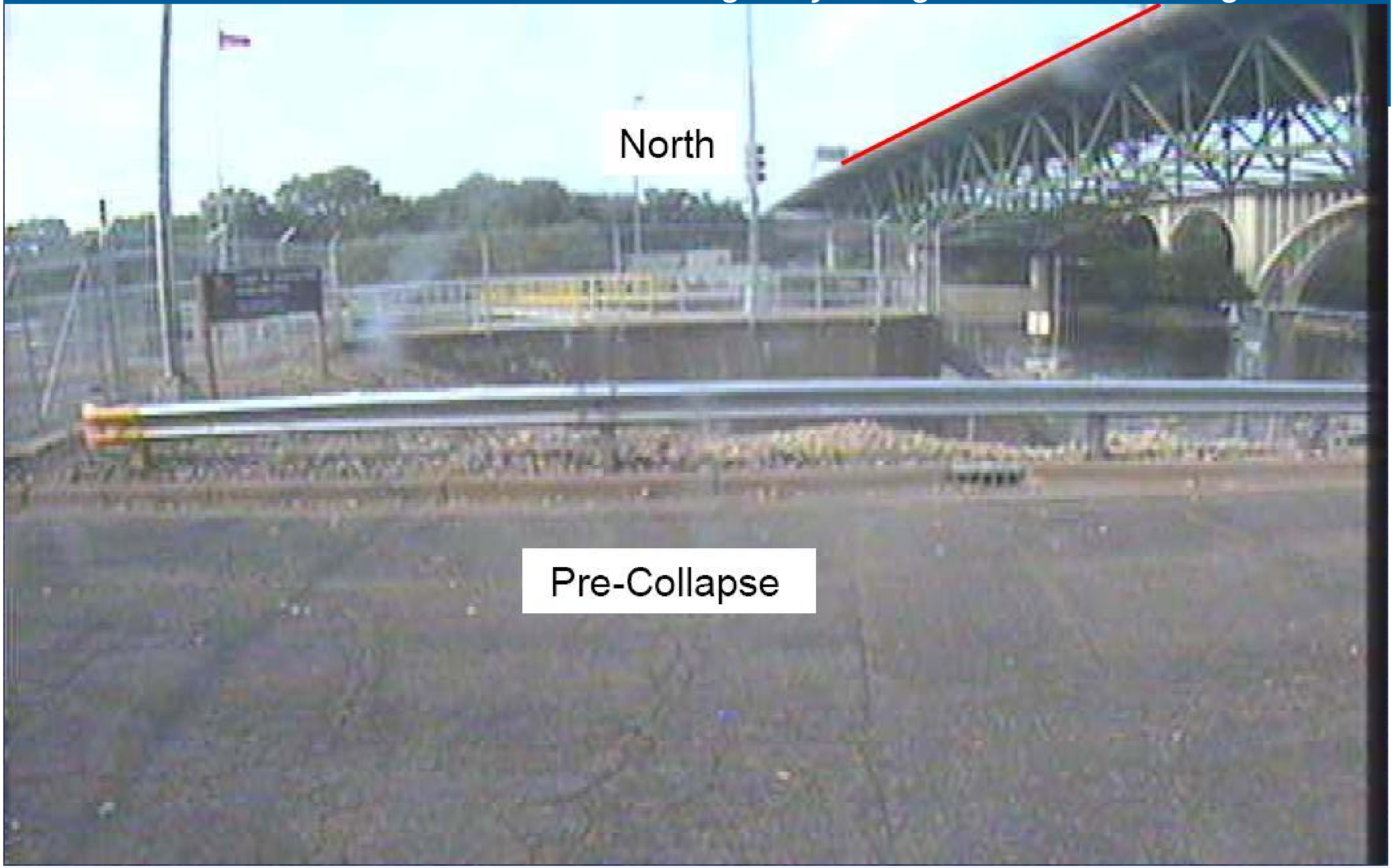
Successful engineering is all about understanding how things break or fail."

Henry Petroski



Collapse of the (steel) I-35W Highway Bridge, Minnesota, Aug 2007

I-35W Highway Bridge, Minnesota, Aug 2007



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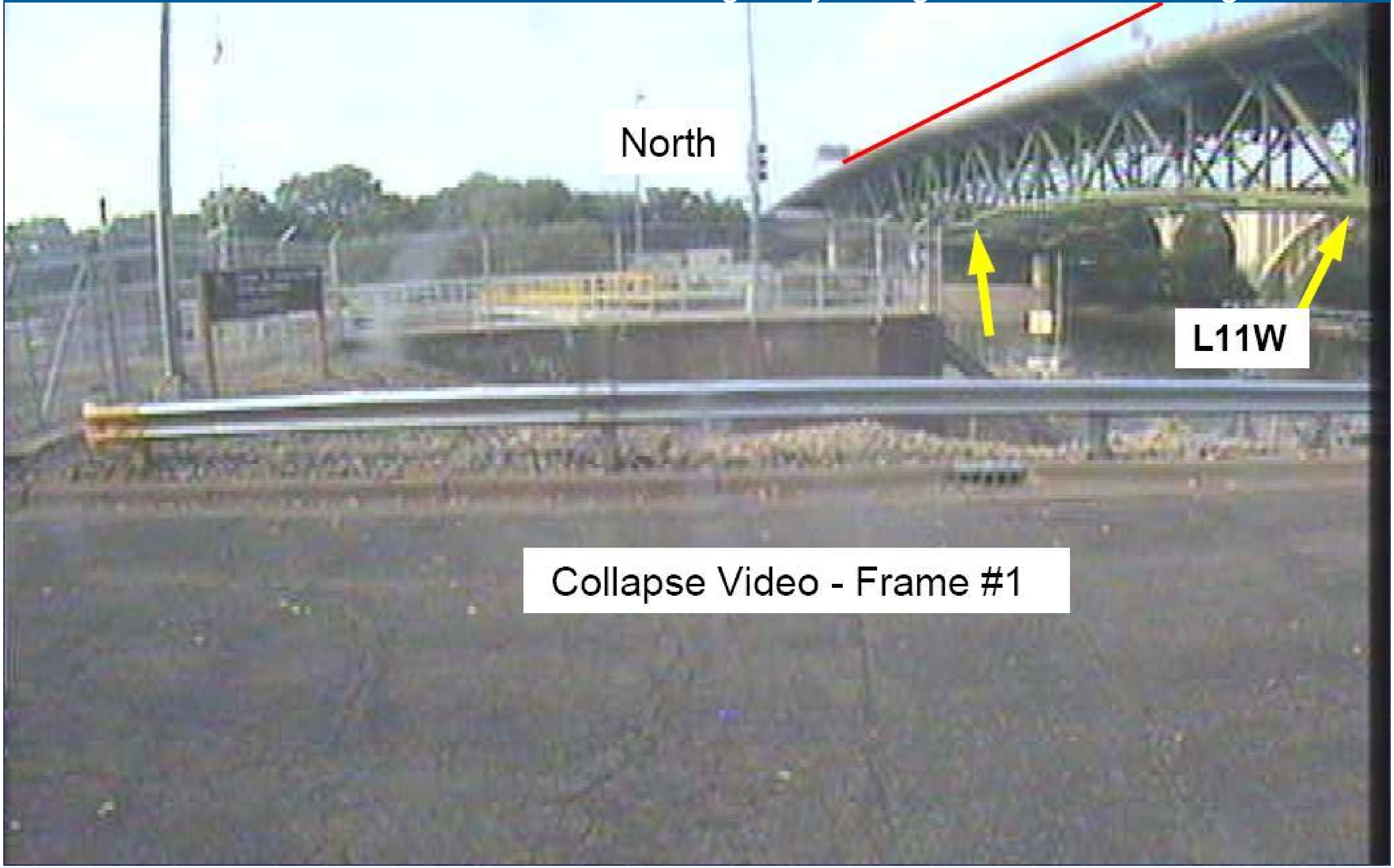
I-35W Highway Bridge, Minnesota, Aug 2007



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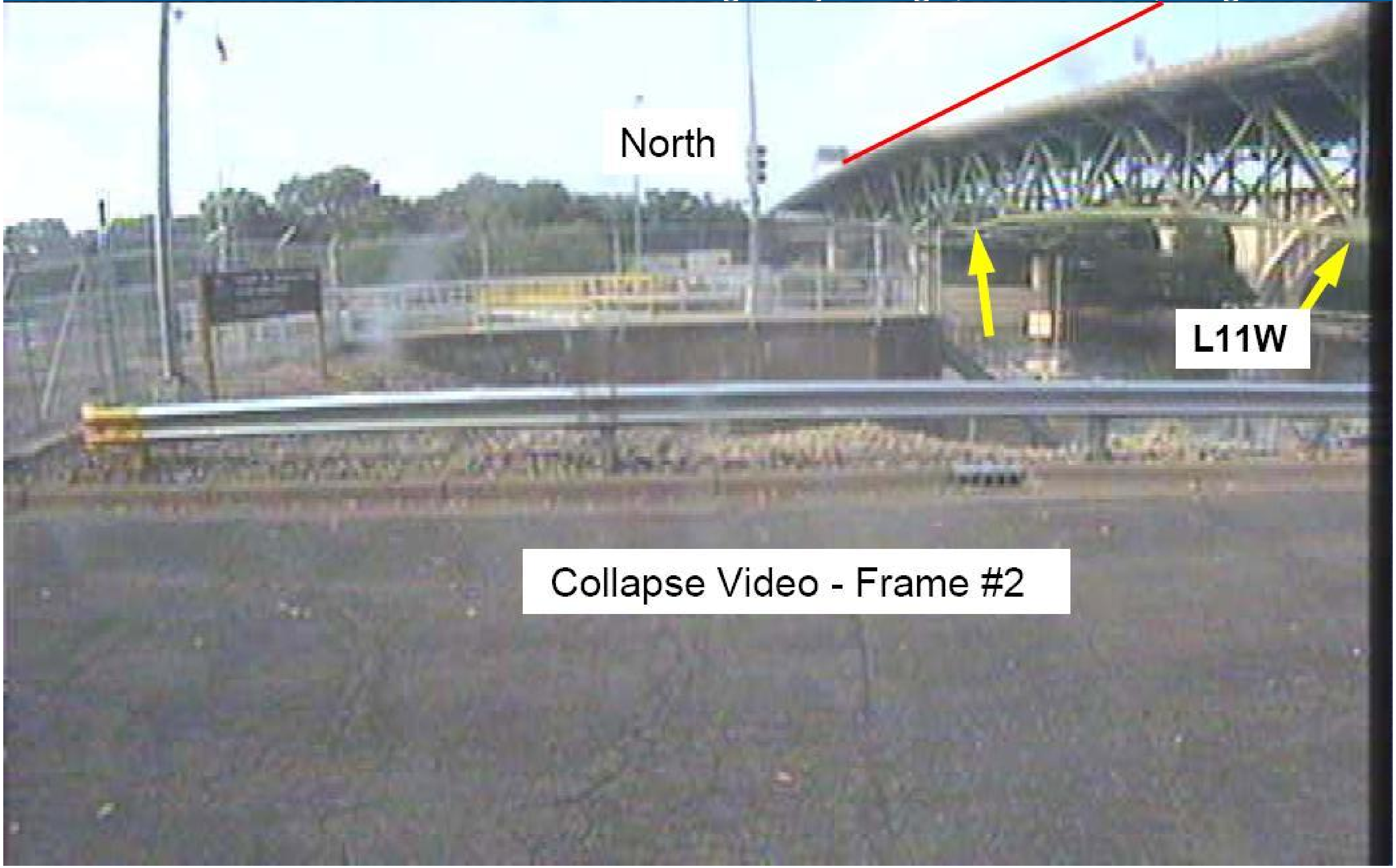
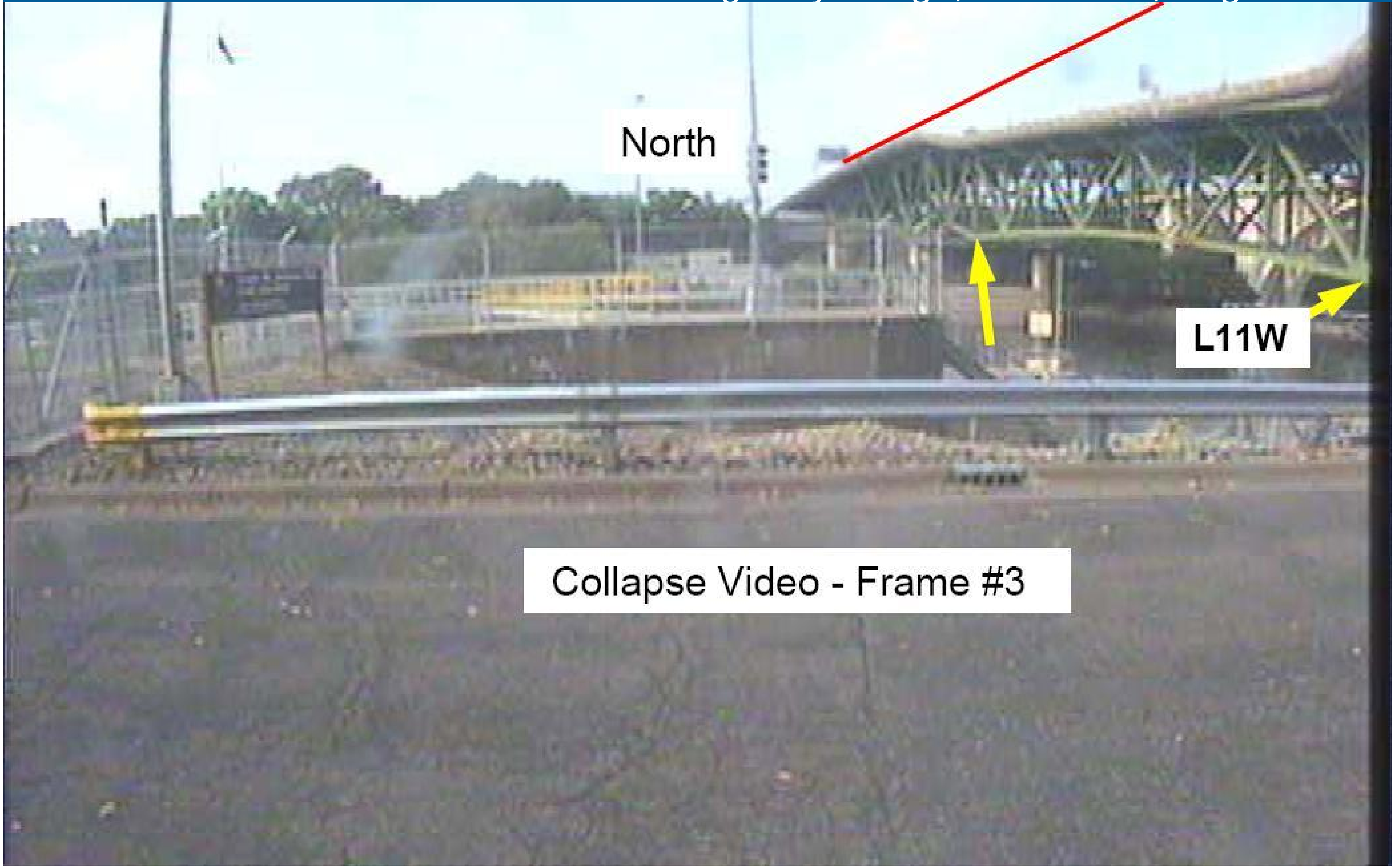
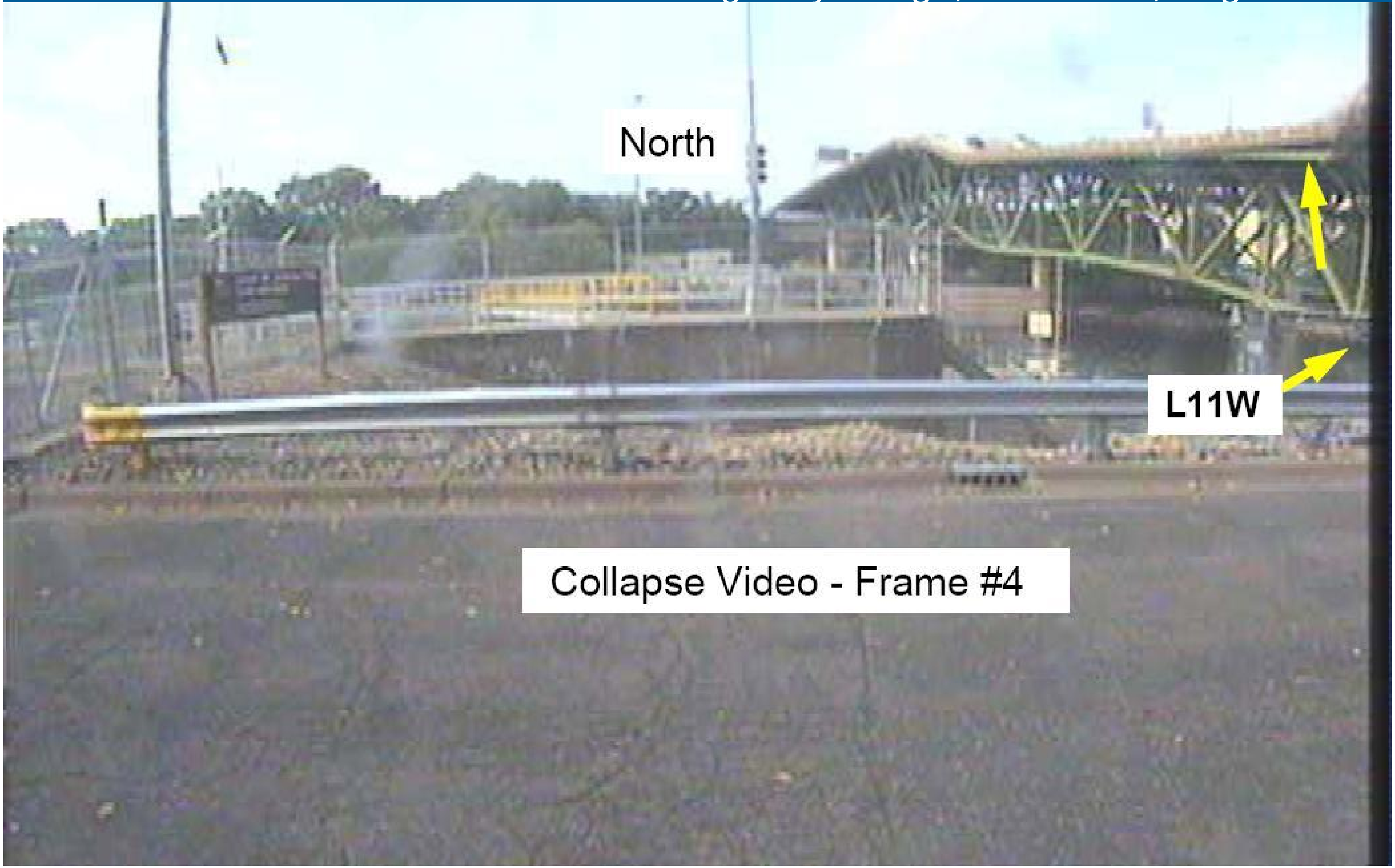
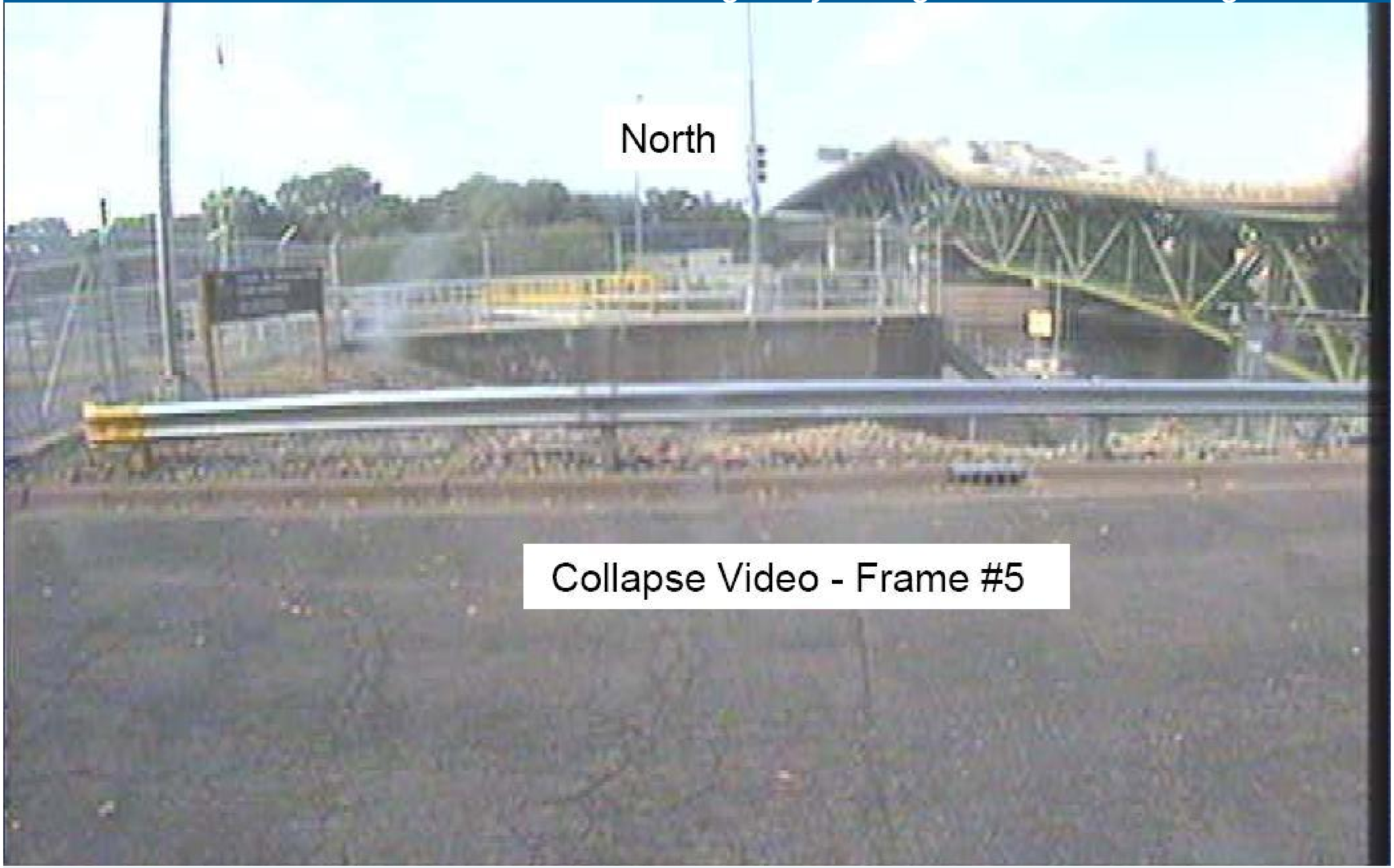

North
L11W
Collapse Video - Frame #2

I-35W Highway Bridge, Minnesota, Aug 2007

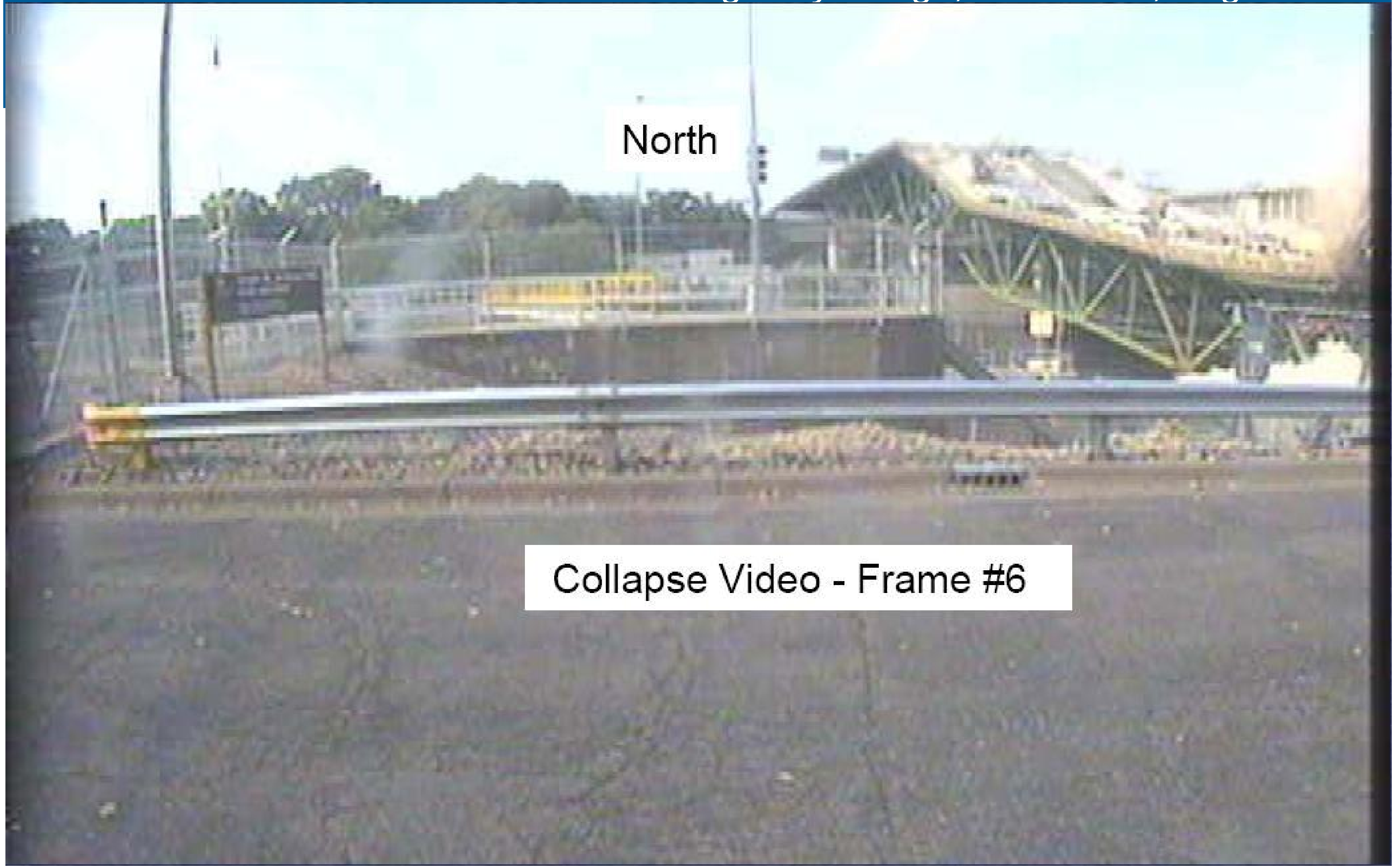



North
L11W
Collapse Video - Frame #4

I-35W Highway Bridge, Minnesota, Aug 2007



I-35W Highway Bridge, Minnesota, Aug 2007



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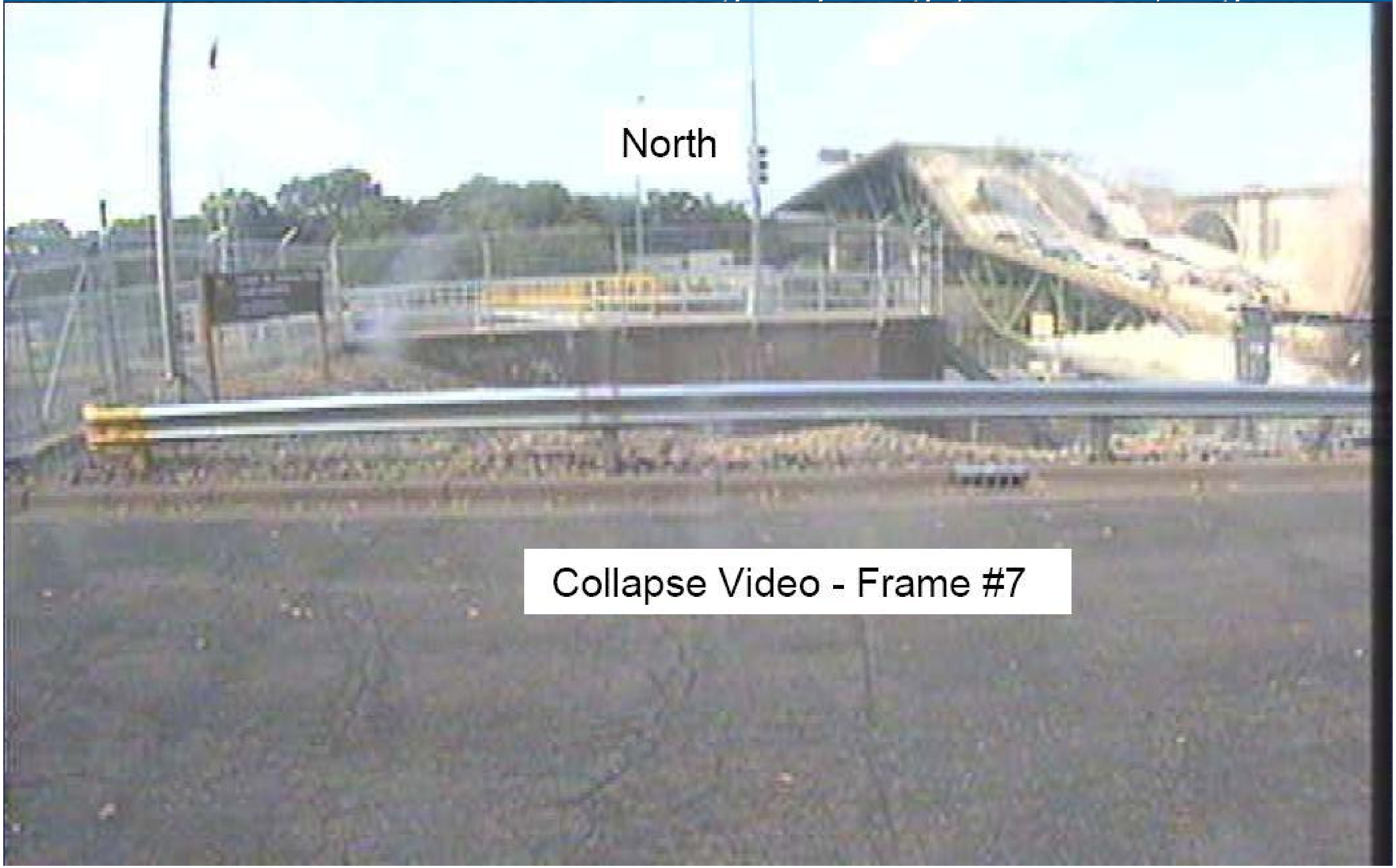
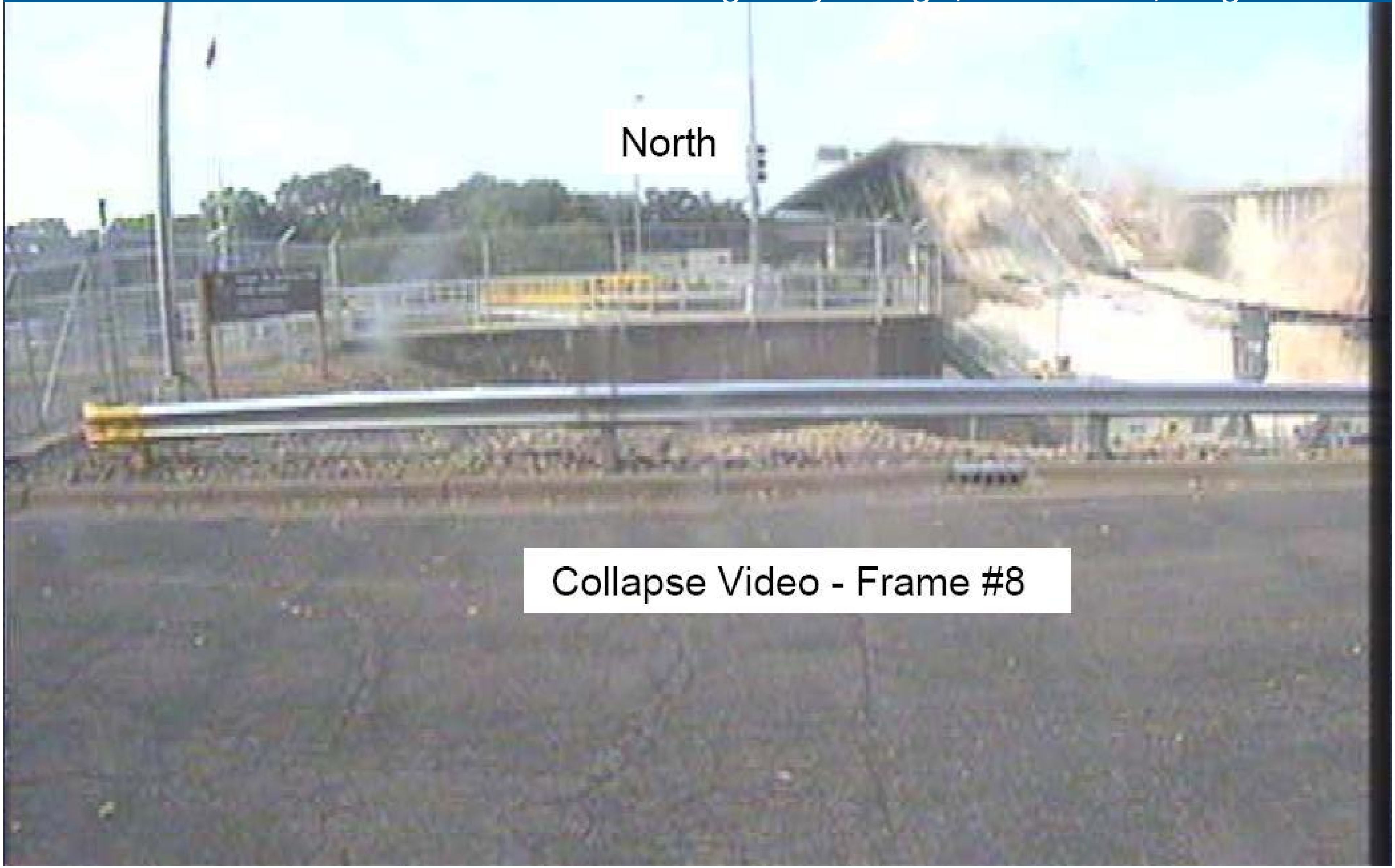
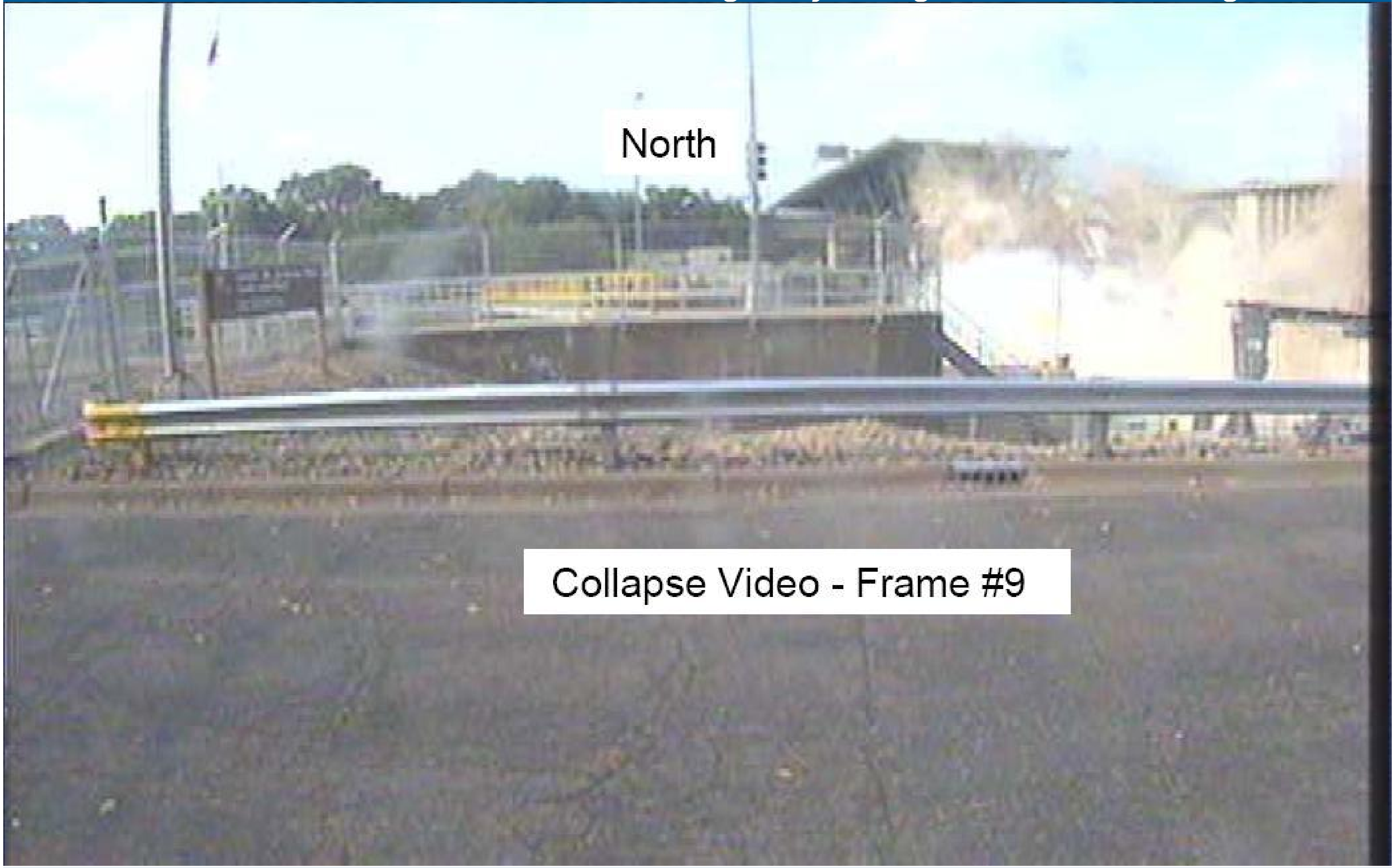
I-35W Highway Bridge, Minnesota, Aug 2007

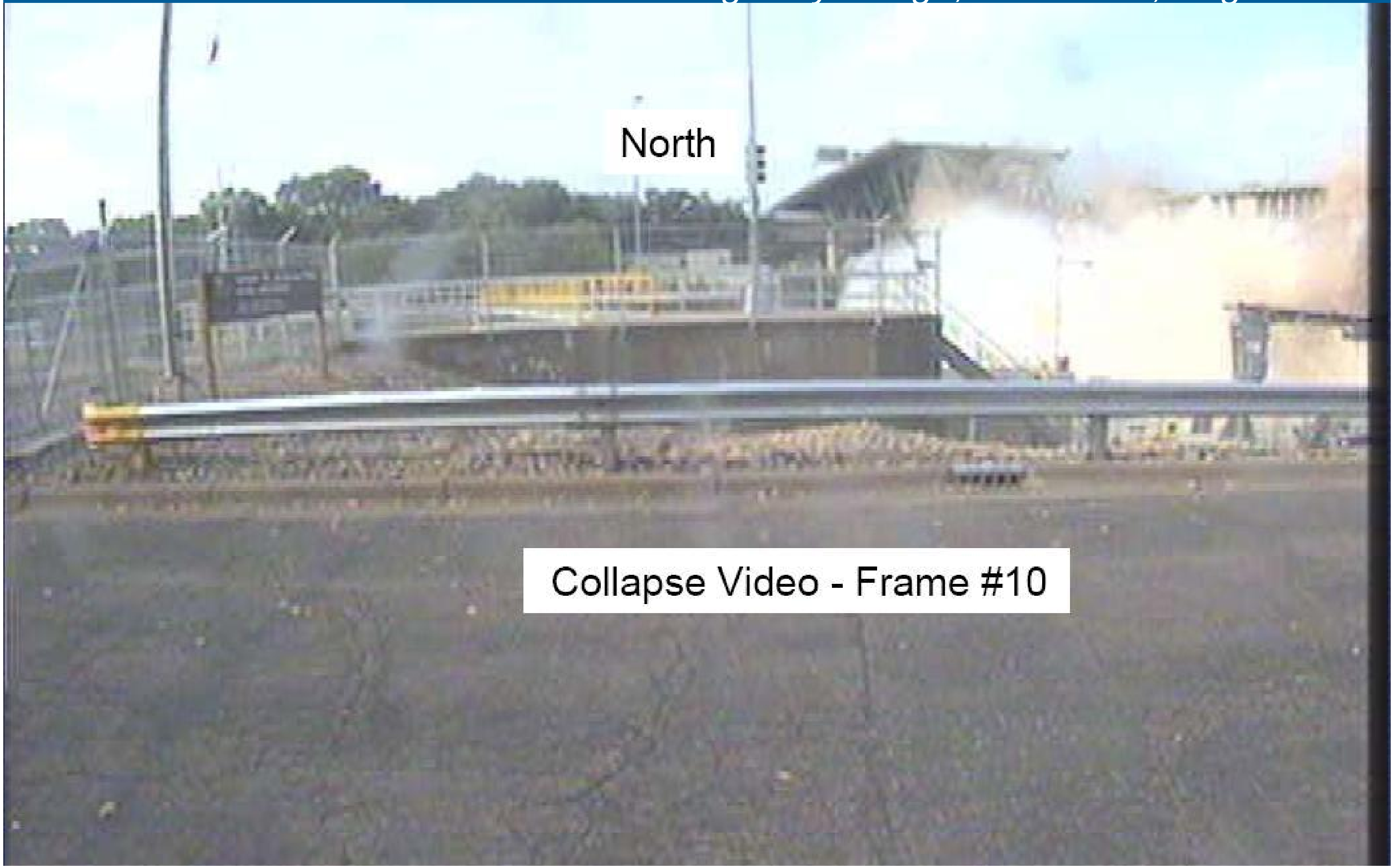


I-35W Highway Bridge, Minnesota, Aug 2007

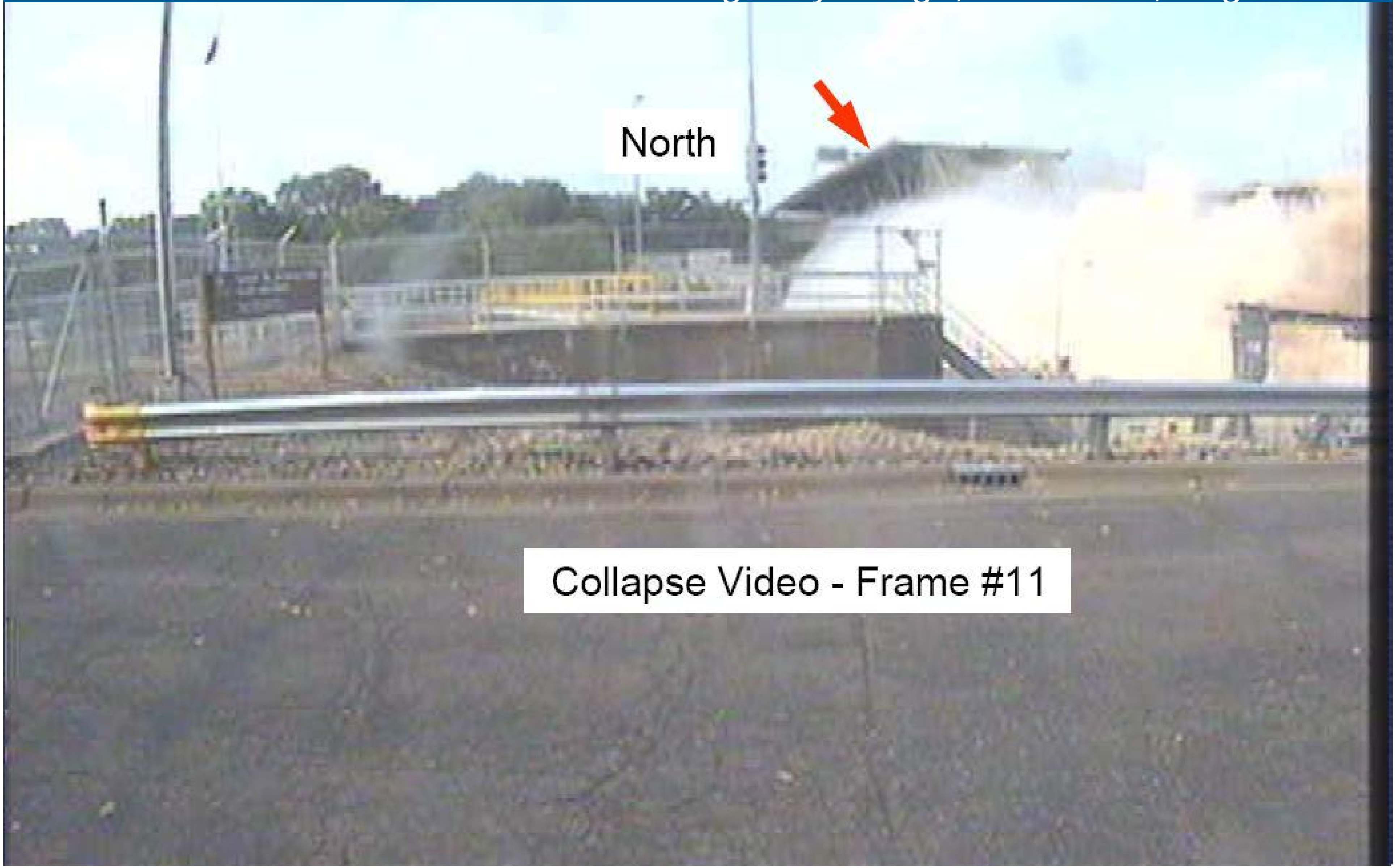



North
Collapse Video - Frame #9

I-35W Highway Bridge, Minnesota, Aug 2007



I-35W Highway Bridge, Minnesota, Aug 2007



Collapse of the (concrete) De la Concorde Overpass, Montreal, 2006

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Inquiries recommended improvements to:

robustness in design

and management of vulnerable structures

How do we apply principles of robustness to FRP structures?

How do we apply principles of robustness to FRP structures?

Not Plastic!

Gaps in design standards

2.1

(2) A structure shall be designed to have adequate:

- *structural resistance,*
- *serviceability, and*
- *durability.*

BS EN1990

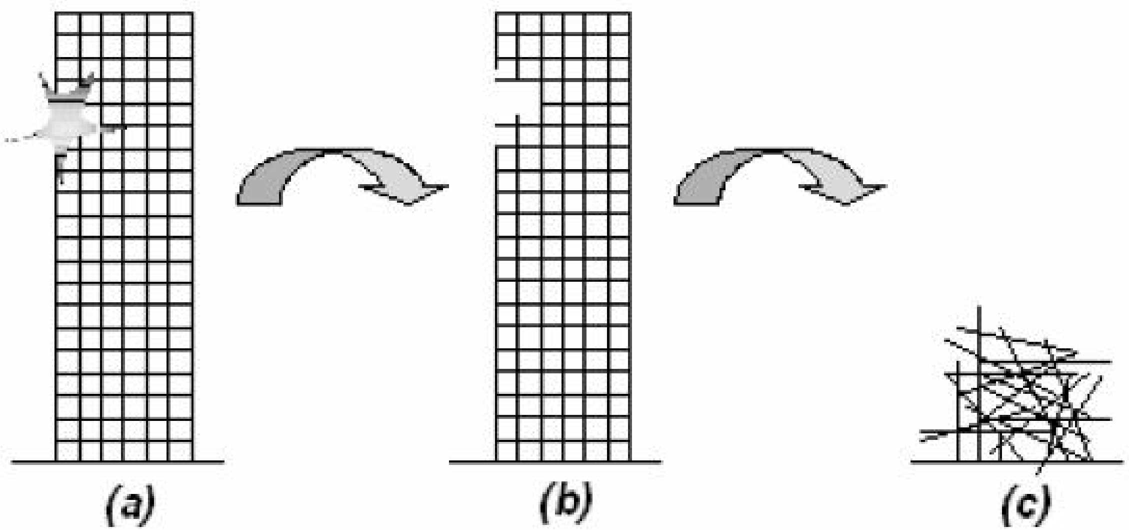
2.4

(2) A structure shall be designed and executed in a way that it will not be damaged by events such as:

- *explosion*
- *impact, and*
- *the consequences of human errors,*

to an extent disproportionate to the original cause

ULS



ULS

In ductile structures, we often rely on a very useful theorem that allows us to make simplifications in the analysis…

ULS

*If the load has a magnitude such that it is possible to find a stress distribution corresponding to stresses within the **yield** surface and satisfying the **equilibrium** conditions and the statical boundary conditions for the actual load, then this load will not be able to cause collapse of the body.*

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The Lower Bound Theorem of Limit Analysis

*If the load has a magnitude such that it is possible to find a stress distribution corresponding to stresses within the **yield** surface and satisfying the **equilibrium** conditions and the statical boundary conditions for the actual load, then this load will not be able to cause collapse of the body.*

The Lower Bound Theorem of Limit Analysis

Not valid without ductility!

ULS

We can not rely on the lower bound theorem for FRP design

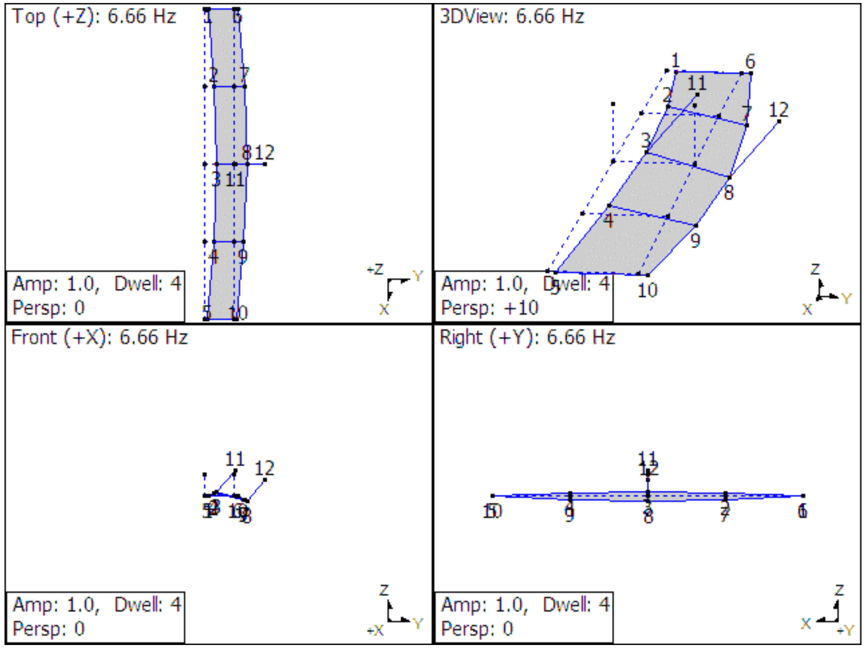
ULS

We can not rely on the lower bound theorem for FRP design

No shortcuts!

Relative stiffness effects	Self equilibrating stresses
Anisotropy	Thermal effects
Shear flexibility	Differential settlement
“Cosmetic” components	

SLS



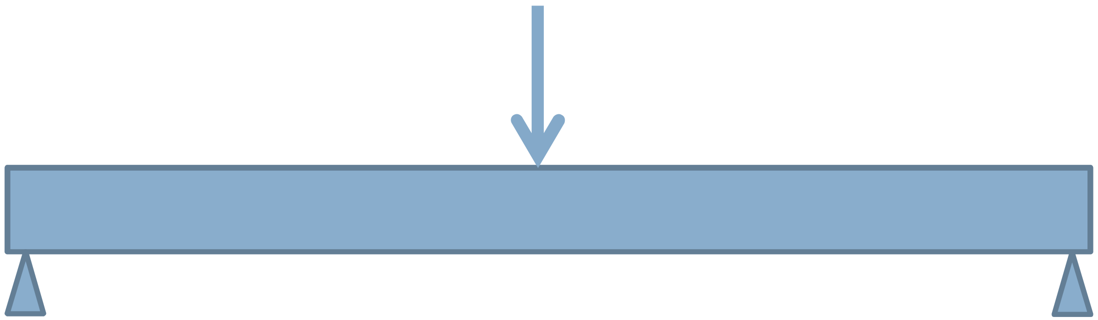
But FRP structure designs are very often governed by SLS criteria

SLS

SLS – driven design is quite unusual in bridge design

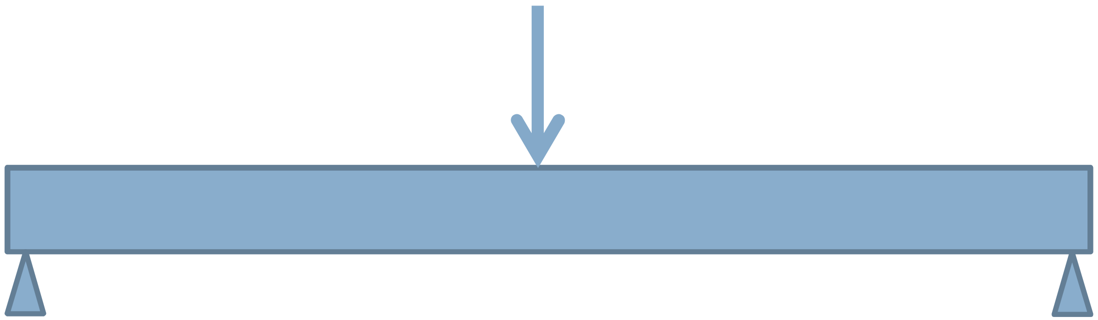
It provides safety and robustness benefits

Consider a simply supported beam, subject to excessive load



SLS

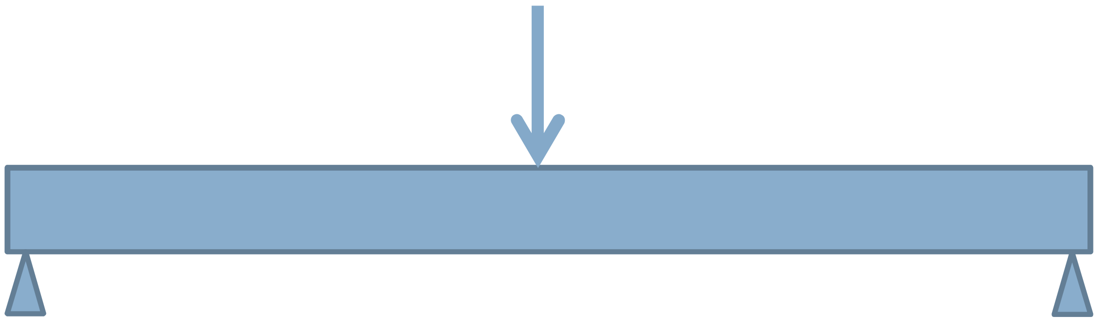
Consider a simply supported beam, subject to excessive load



Steel design, governed by ULS - collapse with almost no warning
- ULS factor of safety R_k/E_k about 1.6

SLS

Consider a simply supported beam, subject to excessive load



Steel design, governed by ULS	- collapse with almost no warning - ULS factor of safety R_k/E_k about 1.6
FRP design, governed by SLS	- large deflections before collapse - ULS factor of safety R_k/E_k about 5-10

Designing for robustness

So how do we design for robustness?

What would happen next if there was some local damage / overstress?

Designing for robustness

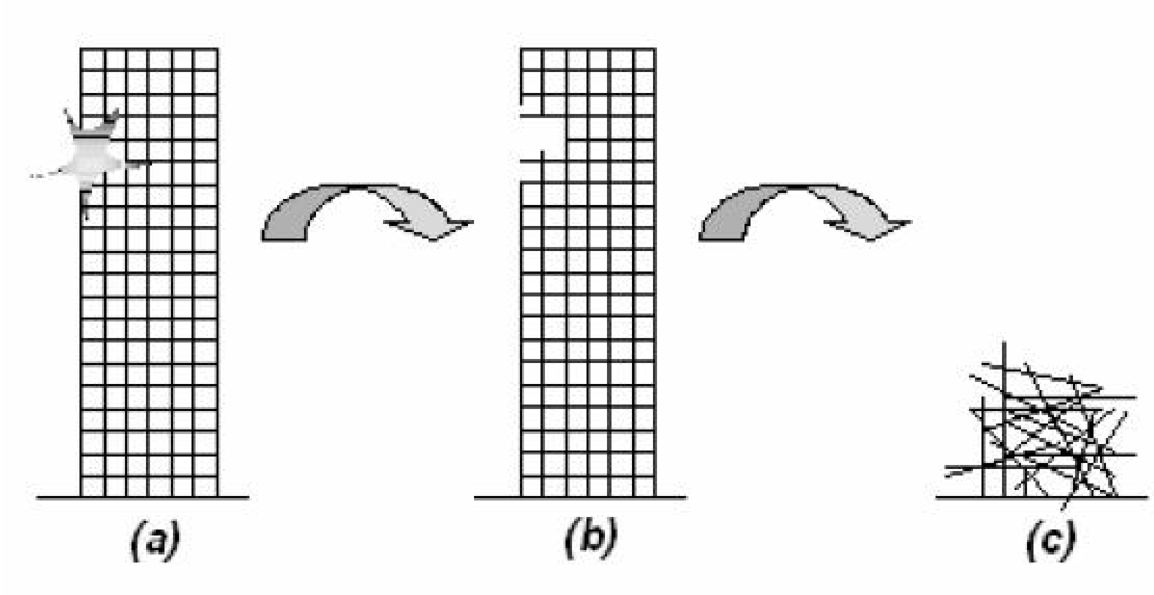
BS EN 1991-1-7 *B.9.1*

(5) For unconventional structures (e.g. very large structures, those with new design concepts, those using new materials) the probability of having some unspecified cause of failure should be considered as substantial. A combined approach of the methods described in B.9.1(2) and B.9.1(3) should be taken into account.

Designing for robustness

BS EN 1991-1-7 *B.9.1*

(5) For unconventional structures (e.g. very large structures, those with new design concepts, those using new materials) the probability of having some unspecified cause of failure should be considered as substantial. A combined approach of the methods described in B.9.1(2) and B.9.1(3) should be taken into account.



Designing for robustness

The undamaged structure is designed for SLS and ULS.

Vulnerable details are identified

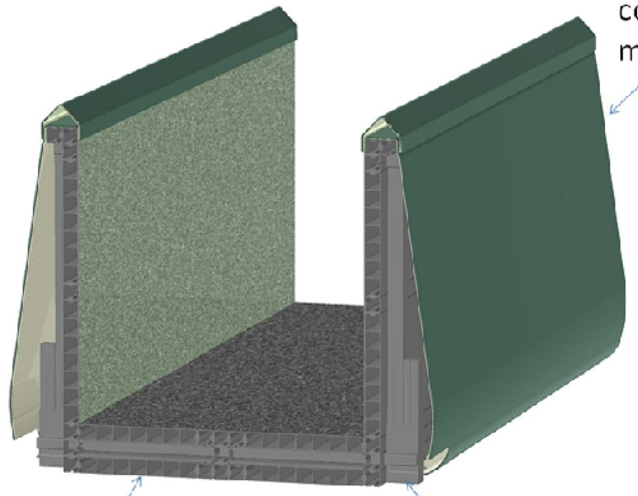
A vulnerable detail is chosen for further investigation

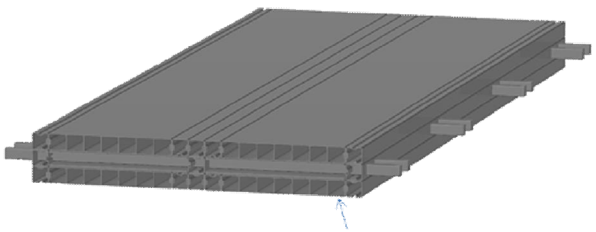
The structure is modelled with this detail removed using the combination of actions for the accidental design situation

The effects from this analysis are compared with the ULS design resistance for short term effects.

If the damaged structure has insufficient resistance, the design is revised to improve robustness.

Designing for robustness





Philosophy developed for St Austell Footbridge

Designing for robustness

Hybrid joints
- Bonded and bolted

Robustness needs to be considered in ALL designs

Challenges are different with FRP

High strain to failure – SLS governs

Framework for design proposed at paper at FRP Bridges 2012.

“Successful engineering is all about understanding how things break or fail."

Henry Petroski

FRP Composites in bridge design

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FRP Composites in bridge design

Most previous designs carried out using combination of:

- (previously) BD37
- (now) Eurocodes for loading and basis of design
- BD90,
- Eurocomp Design Code,
- Product design manuals,
- Project-specific “aspects not covered” or departures (often developed by designers).

Currently no Eurocode for FRP design (there are plans for one eventually).

There is a need for a more coordinated and comprehensive set of design rules and principles.

New developments in design guidance

FRP Composites in bridge design

NGCC has an FRP Bridge Design Group

Producing design guidance on FRP bridge design

-Eurocode aligned

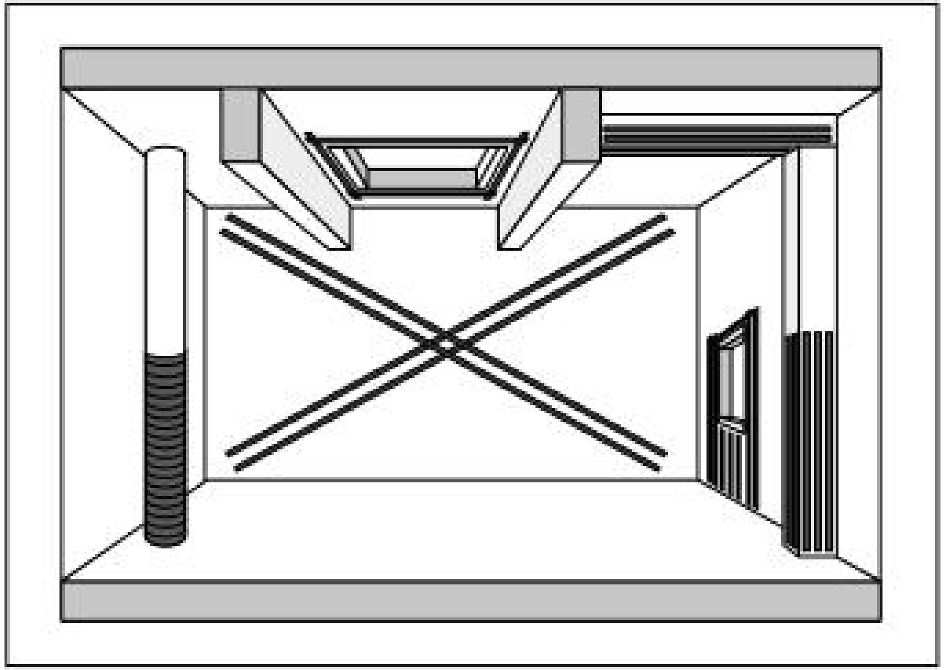
-Aims to plug the gaps in current standards and provide best practice guidance

-Focus on principles and failure criteria to be covered.

Strengthening using FRP: new edition of TR55

What does TR55 cover?

How has it changed in 3rd edition?



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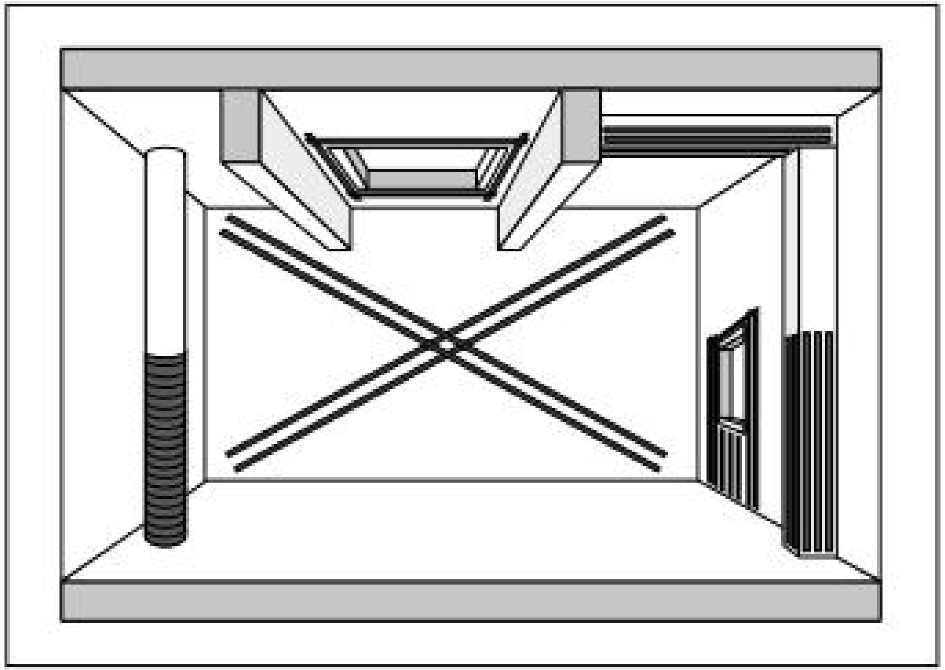


What does TR55 cover?

1 Introduction
2 Background
3 Material types and properties
4 Review of applications
5 Structural design of strengthened members
6 Strengthening members in flexure
7 Shear strengthening
8 Strengthening axially loaded members
9 Emerging technologies
10 Workmanship and installation
11 Long term inspection and monitoring

What does TR55 cover?

2 Background

- Advantages
- Disadvantages

What does TR55 cover?

3 Material types and properties

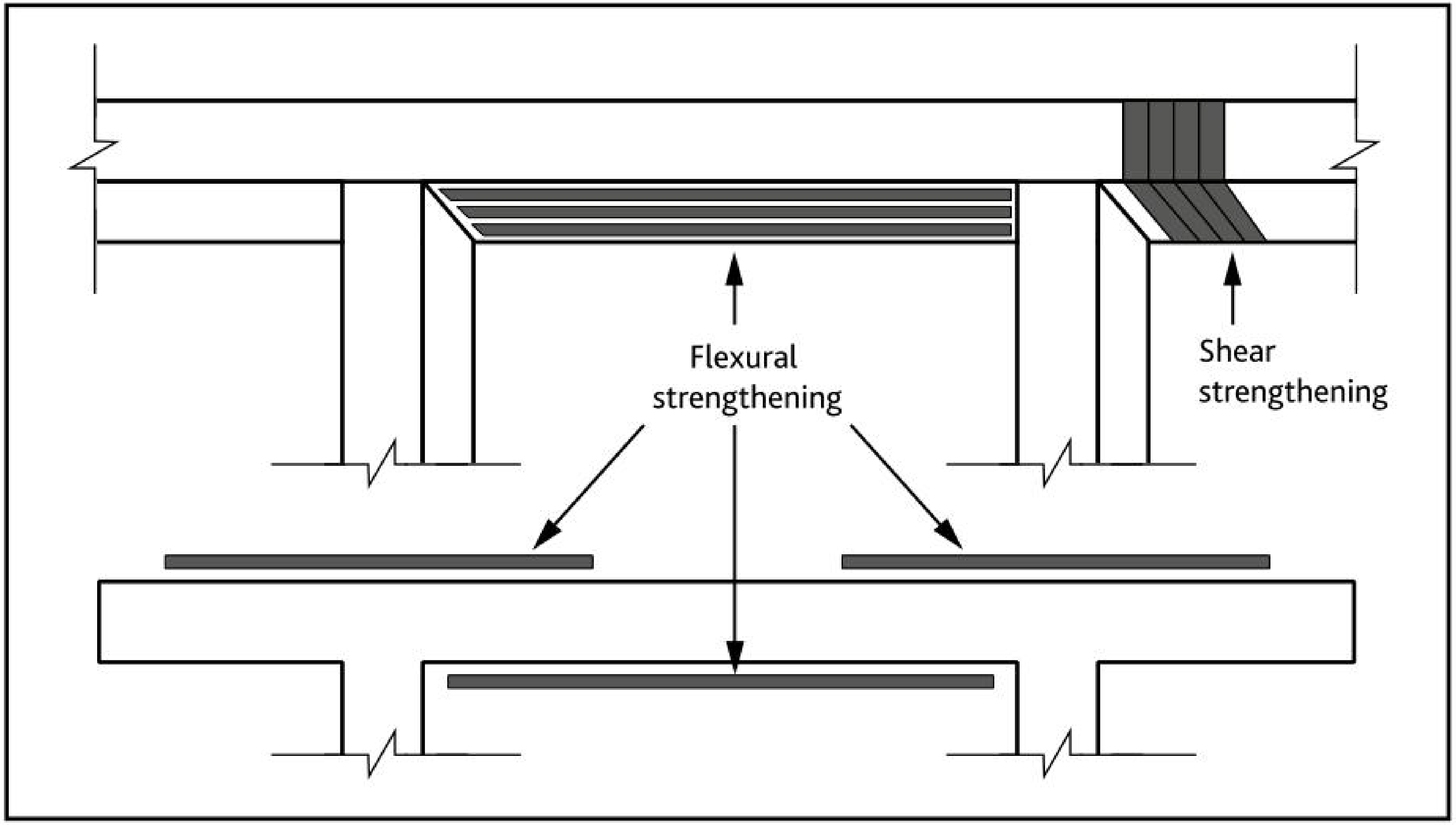
- Fibres
- Fabrics
- Plates
- Rods and strips
- Preformed shells
- Specials
- Adhesives and resins

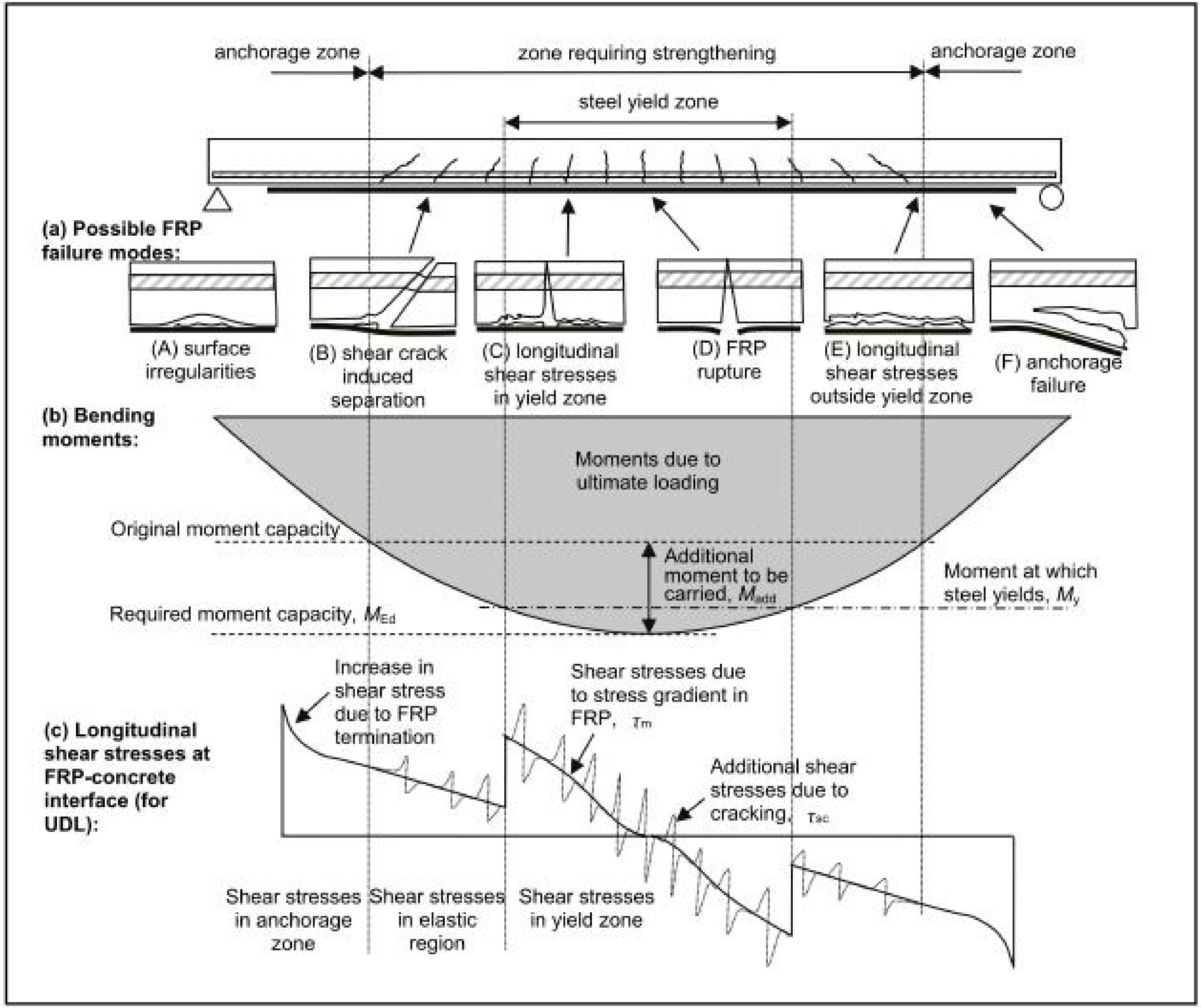
What does TR55 cover?

5 Structural design of strengthened members

Ultimate	Serviceability
Structural strength	Deflection
Bending	Concrete crack widths
Shear	Stress limitations
Compression	Vibration
Anchorage–plate separation	
FRP stress rupture	
Fatigue	
Fire	

What does TR55 cover?

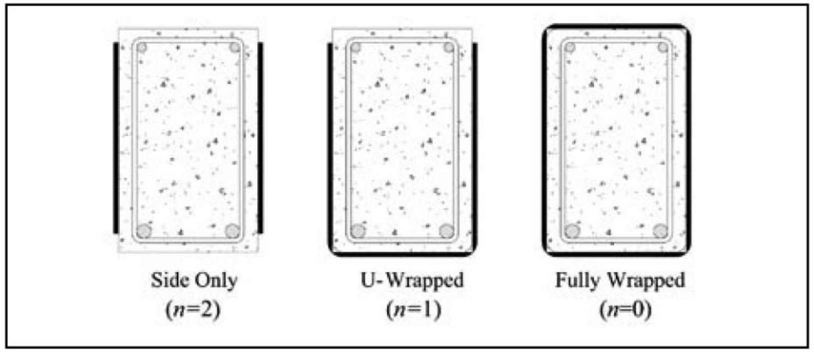


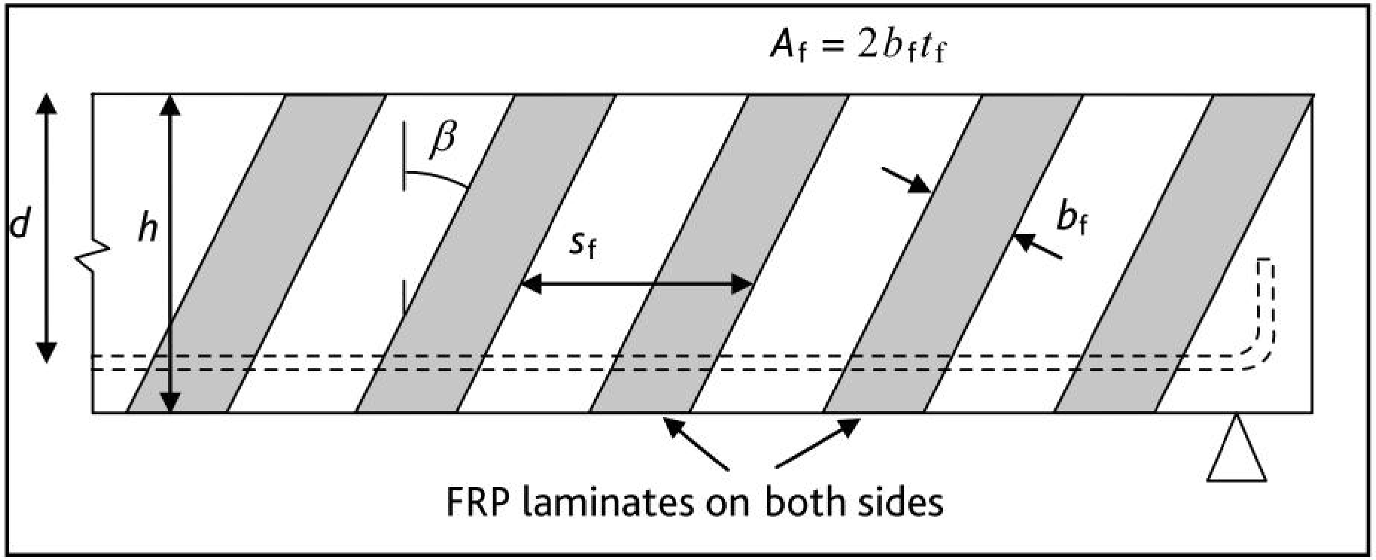


anchorage zone
zone requiring strengthening
anchorage zone
steel yield zone
(a) Possible FRP failure modes:
(A) surface irregularities
(B) shear crack induced separation
(C) longitudinal shear stresses in yield zone
(D) FRP rupture
(E) longitudinal shear stresses outside yield zone
(F) anchorage failure
(b) Bending moments:
Moments due to ultimate loading
Original moment capacity
Additional moment to be carried, M_{add}
Moment at which steel yields, M_y
Required moment capacity, M_{Ed}
(c) Longitudinal shear stresses at FRP-concrete interface (for UDL):
Increase in shear stress due to FRP termination
Shear stresses due to stress gradient in FRP, τ_m
Additional shear stresses due to cracking, τ_{ac}
Shear stresses in anchorage zone
Shear stresses in elastic region
Shear stresses in yield zone

What does TR55 cover?

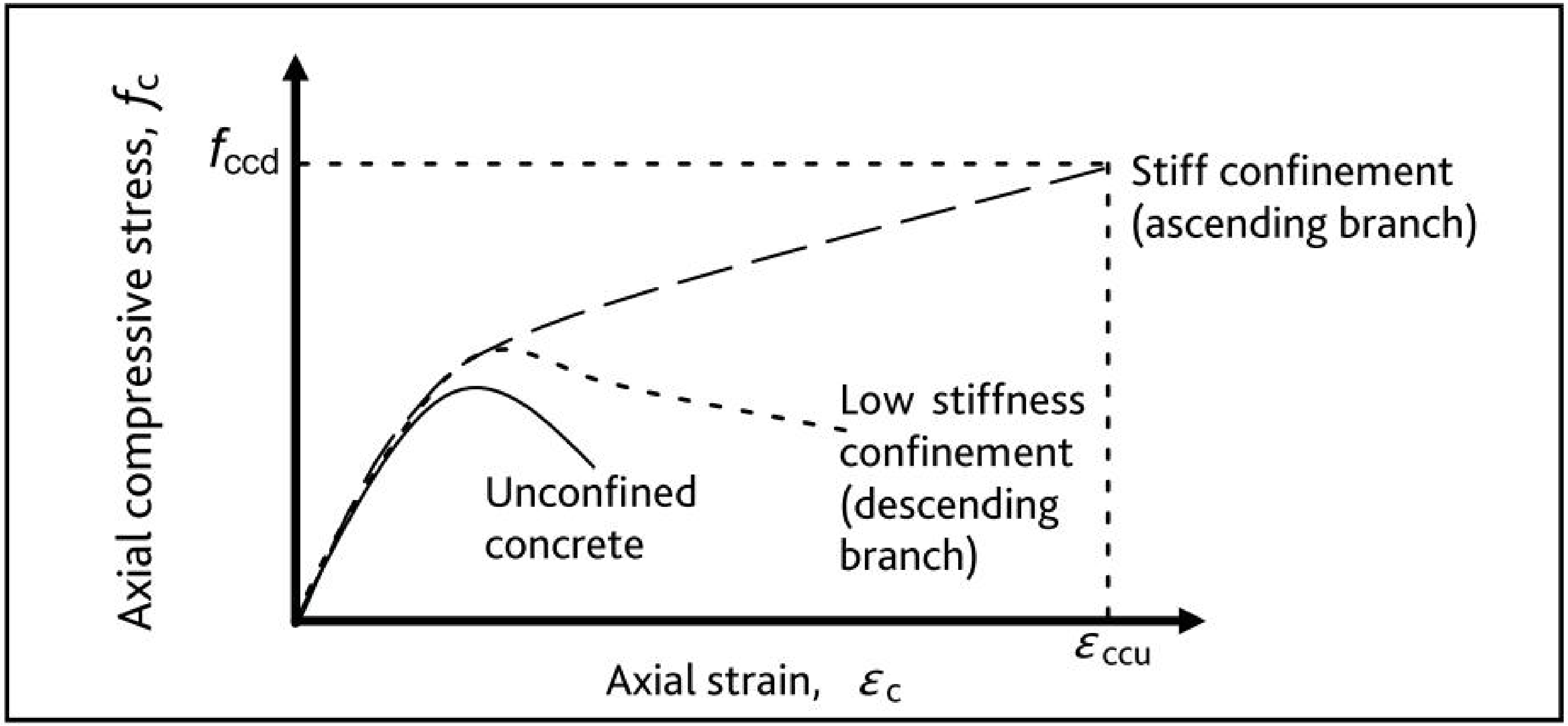
7 Shear strengthening





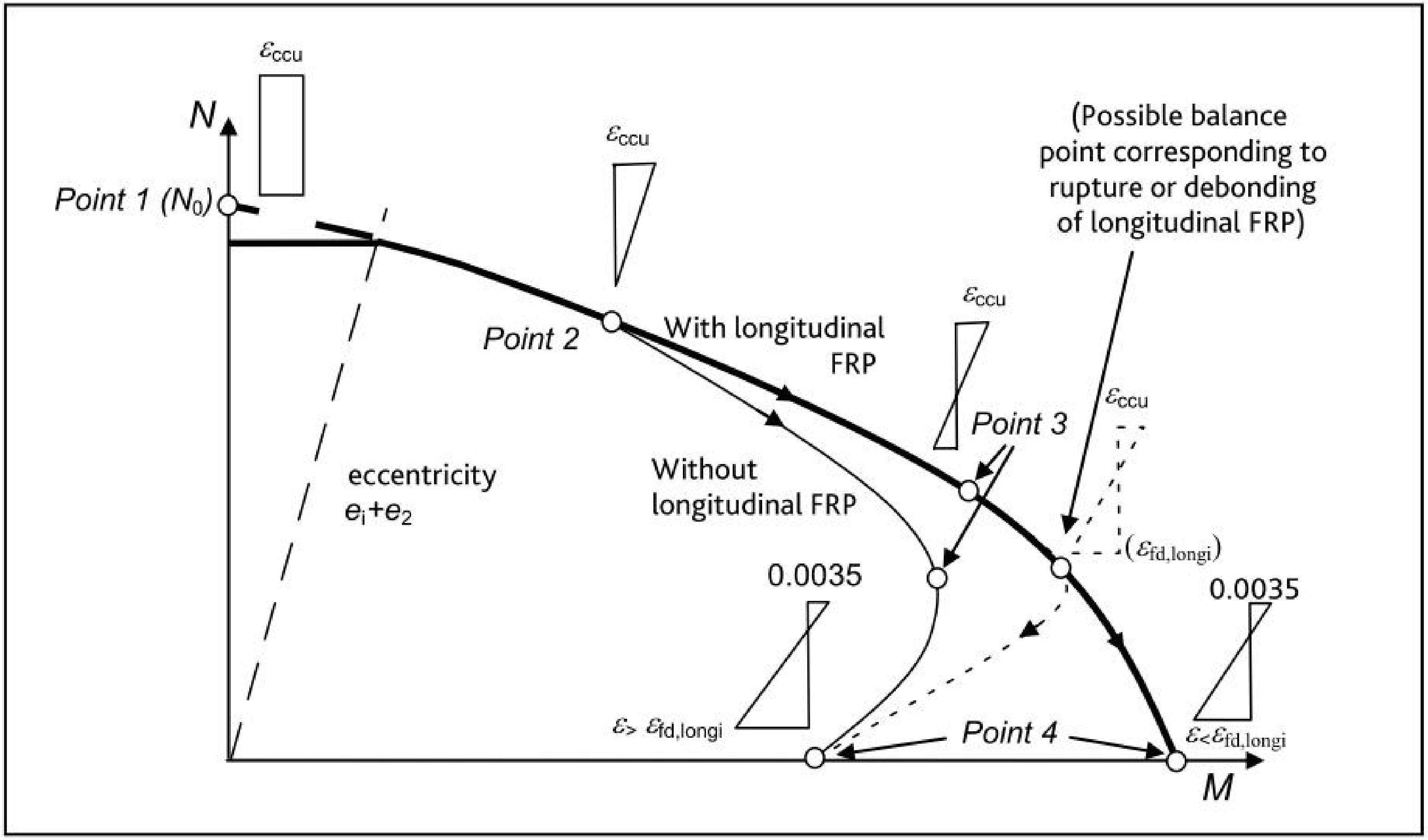
What does TR55 cover?

8 Strengthening axially loaded members



What does TR55 cover?

8 Strengthening axially loaded members



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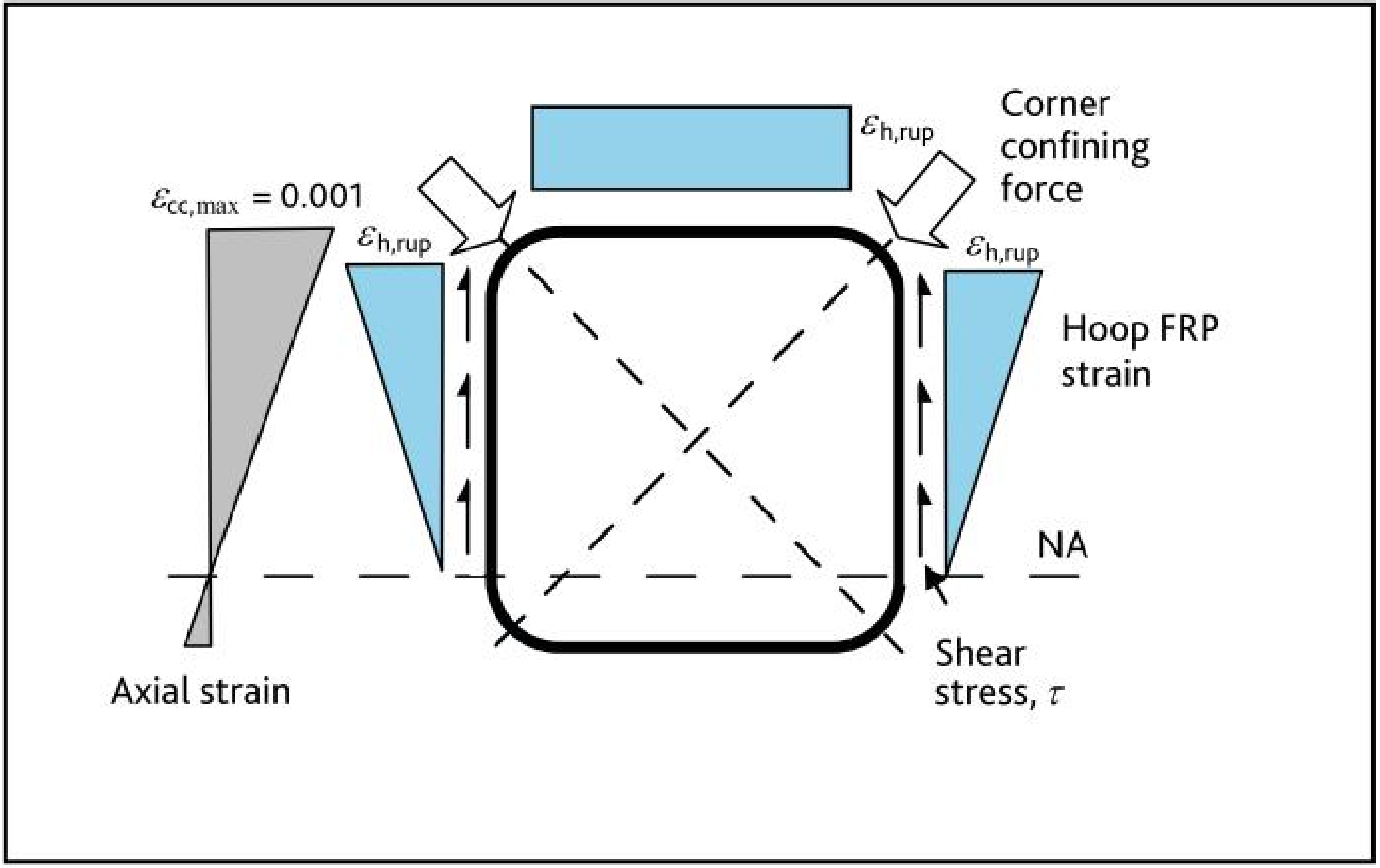
What does TR55 cover?

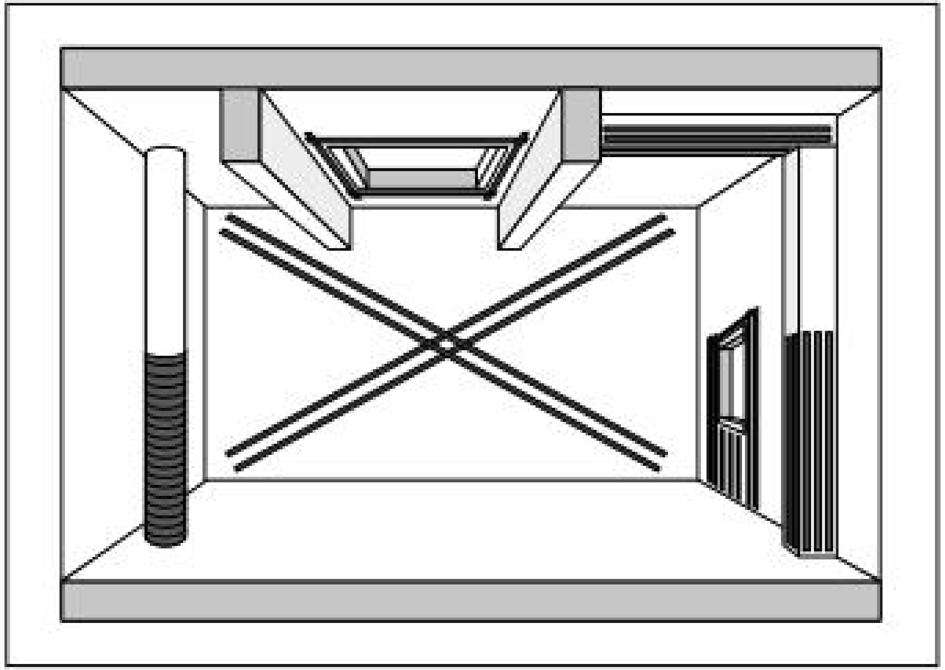
8 Strengthening axially loaded members

Square and rectangular columns:



What does TR55 cover?

How has it changed in 3rd edition?



How has it changed in the 3rd edition?

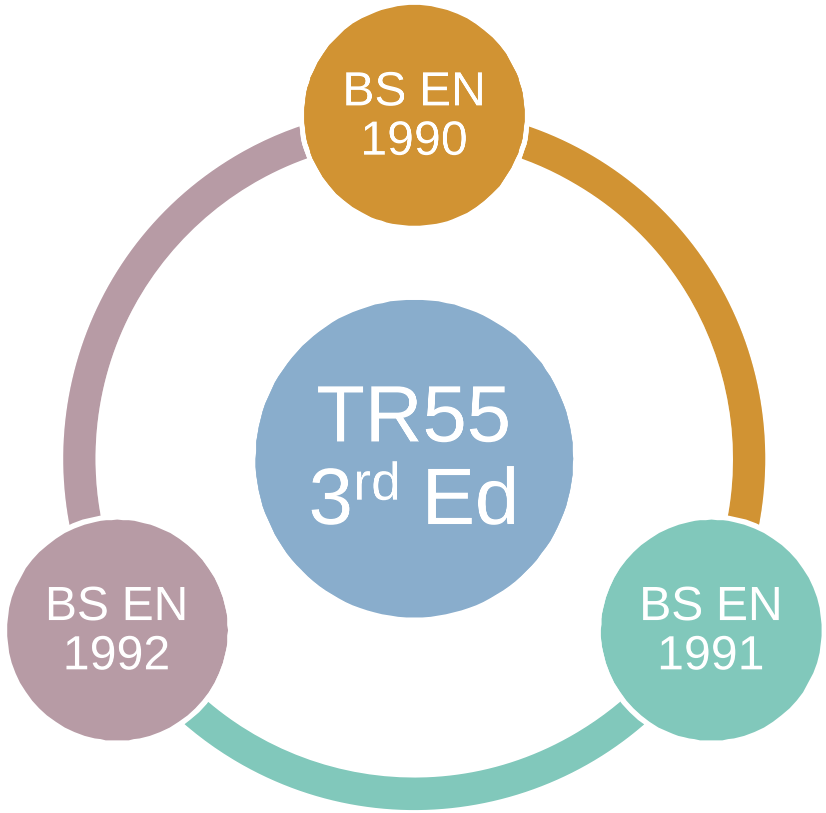
- Eurocode alignment
- Research advances
- Further experience of materials
- Links to CompClass & CSWIP

How has it changed in the 3rd edition?

- Fire design
- Improvements and rationalisation of design processes
- Deep embedment bars
- Emerging technologies

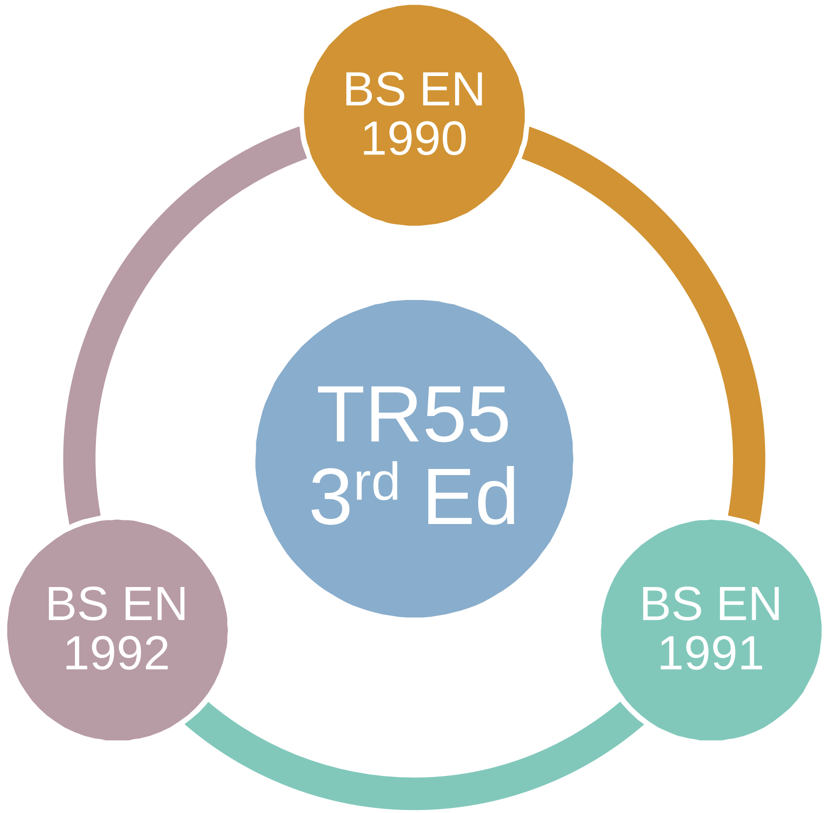
How has it changed in the 3rd edition?

- Eurocode alignment
  - Eurocodes have effectively replaced British Standards for design.
  - FRP outside scope of Eurocodes



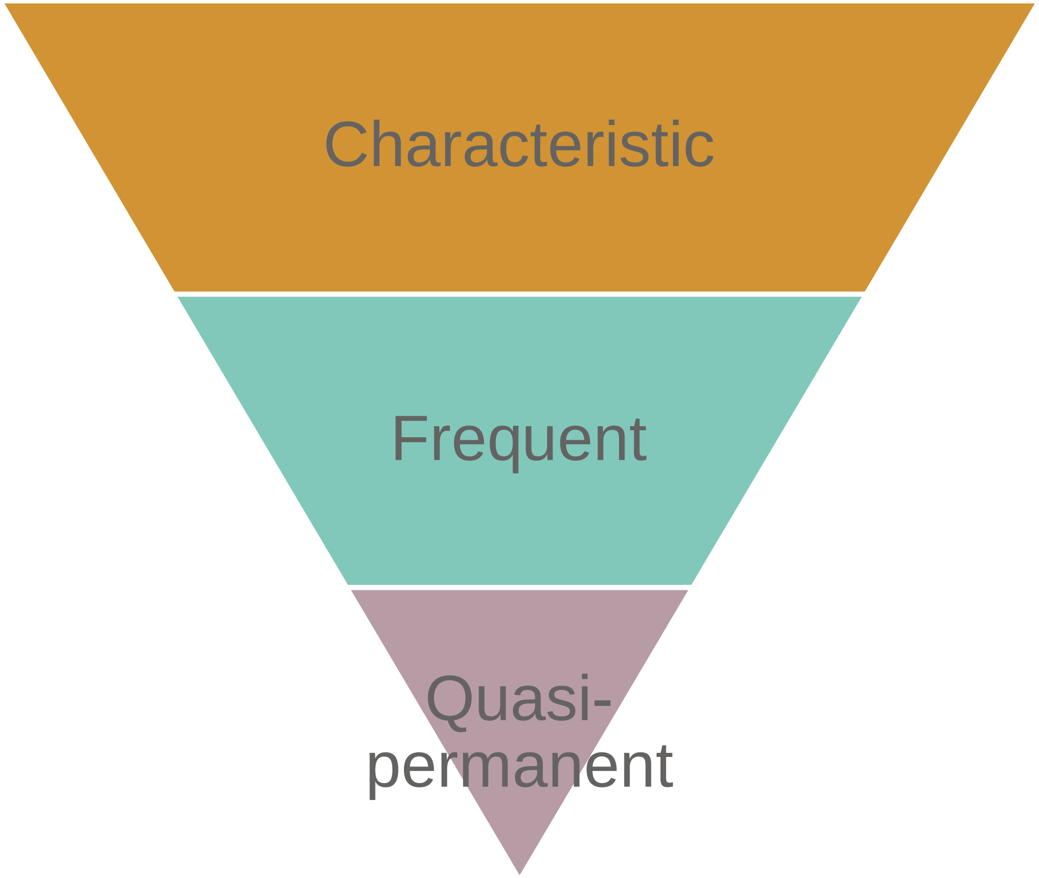
How has it changed in the 3rd edition?

- Eurocode alignment
- Particular impact on:
  - Basis of design
  - Load models
  - Concrete



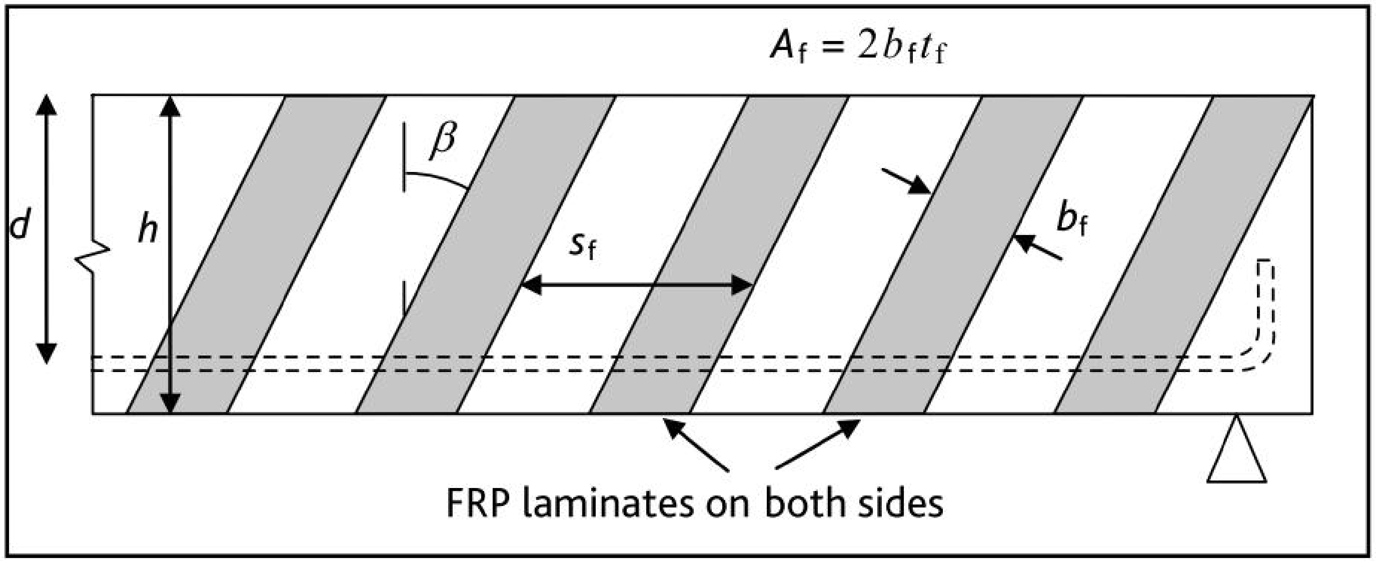
How has it changed in the 3rd edition?

- Eurocode alignment
- Particular impact on:
  - Combinations of actions
  - Robustness
  - Initial strain
  - SLS criteria



How has it changed in the 3rd edition?

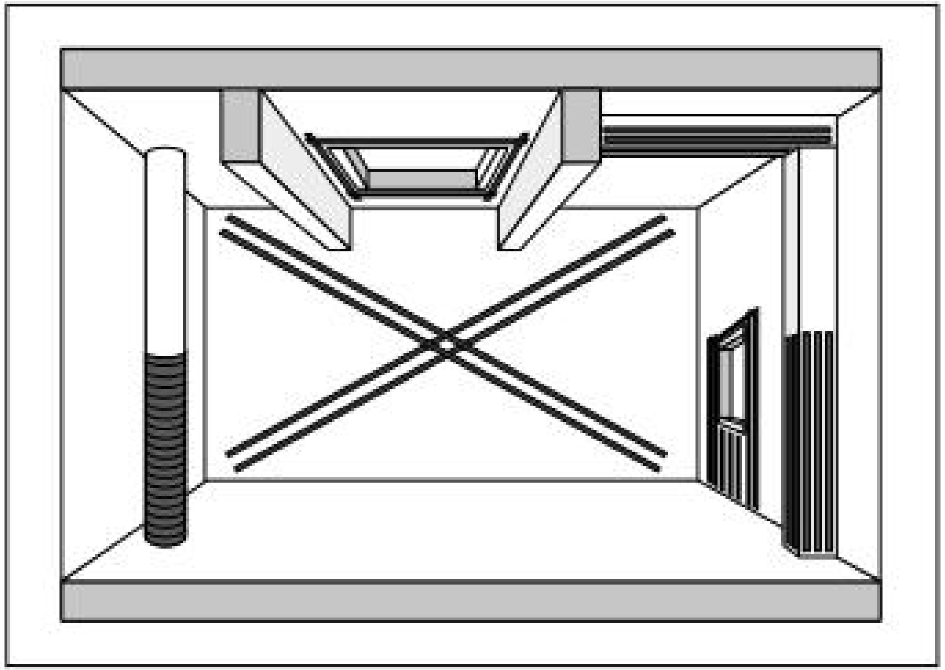
- Eurocode alignment
- Particular impact on:
  - Fire design
  - Shear strengthening



Conclusion

What does TR55 cover?

How has it changed in 3rd edition?



Agenda

What is NGCC?

What are FRP Composites?

Why use them in bridges?

What have we learned so far?

What challenges remain?

Recent developments in design guidance

Future opportunities

Future opportunities

FRP Composites in bridge design

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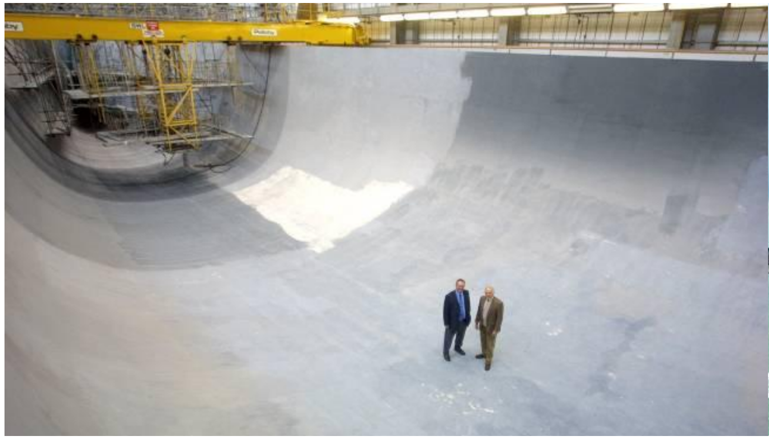
Future opportunities

FRP Composites in bridge design



Mirabella V 75m long hull mould & on sea trials

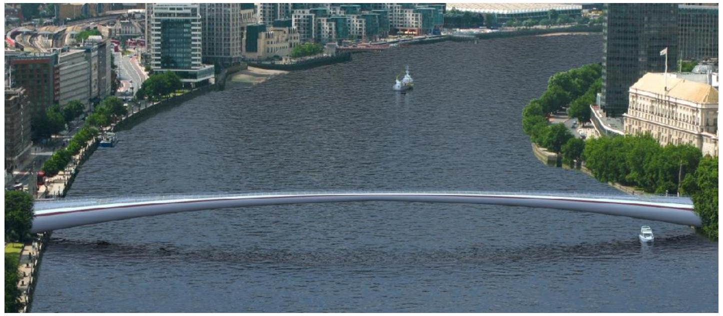
(VT Shipbuilding)

75m long wind turbine blade

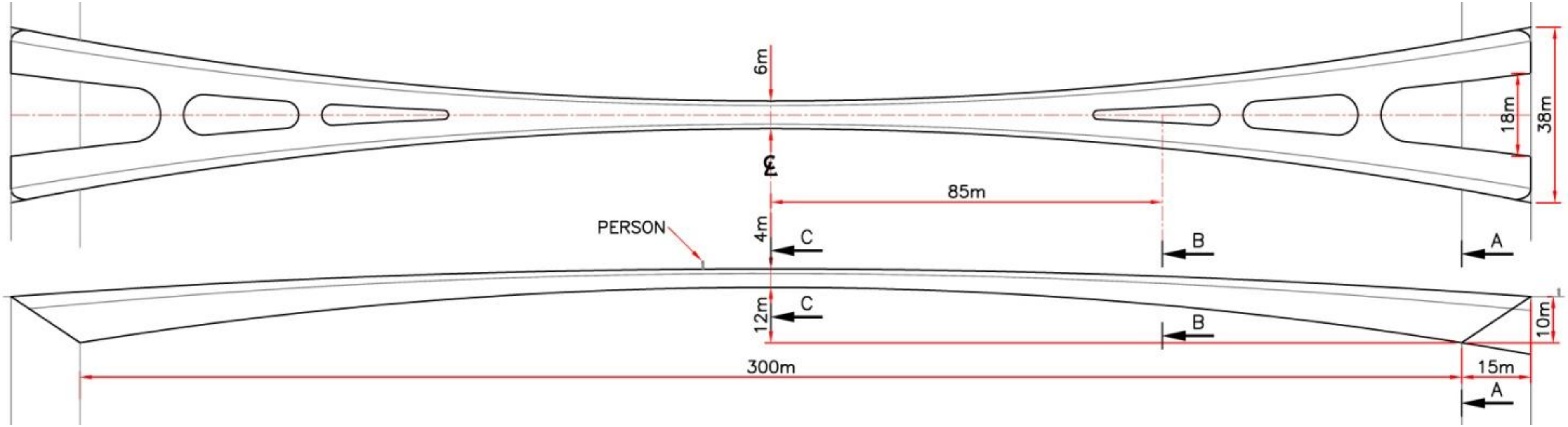
(Reinforced Plastics / Seimens)

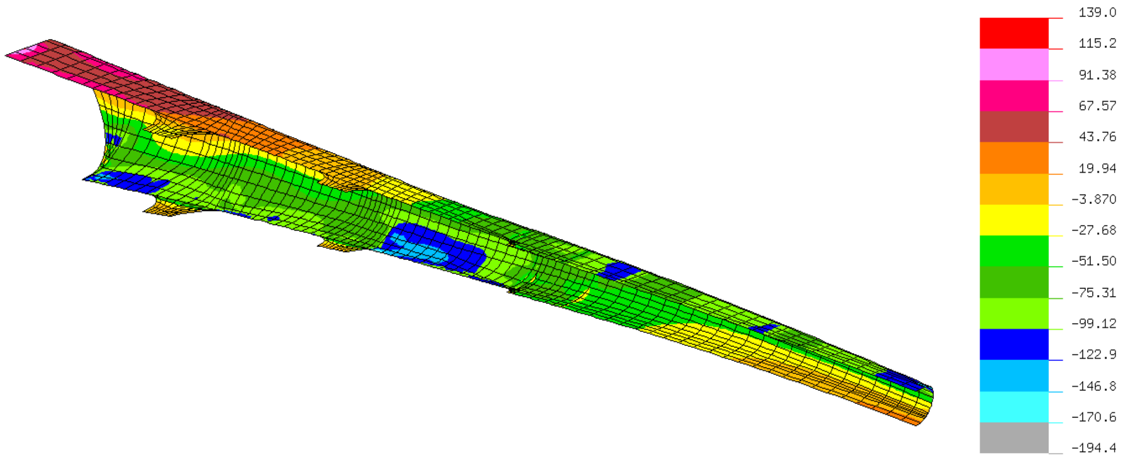
FRP Composites in bridge design

- Most conventional bridges would have 2 or more intermediate piers.
- Piers are complex, expensive & time consuming to build
- FRP design to have 300m clear span to avoid the need for piers.



FRP Composites in bridge design





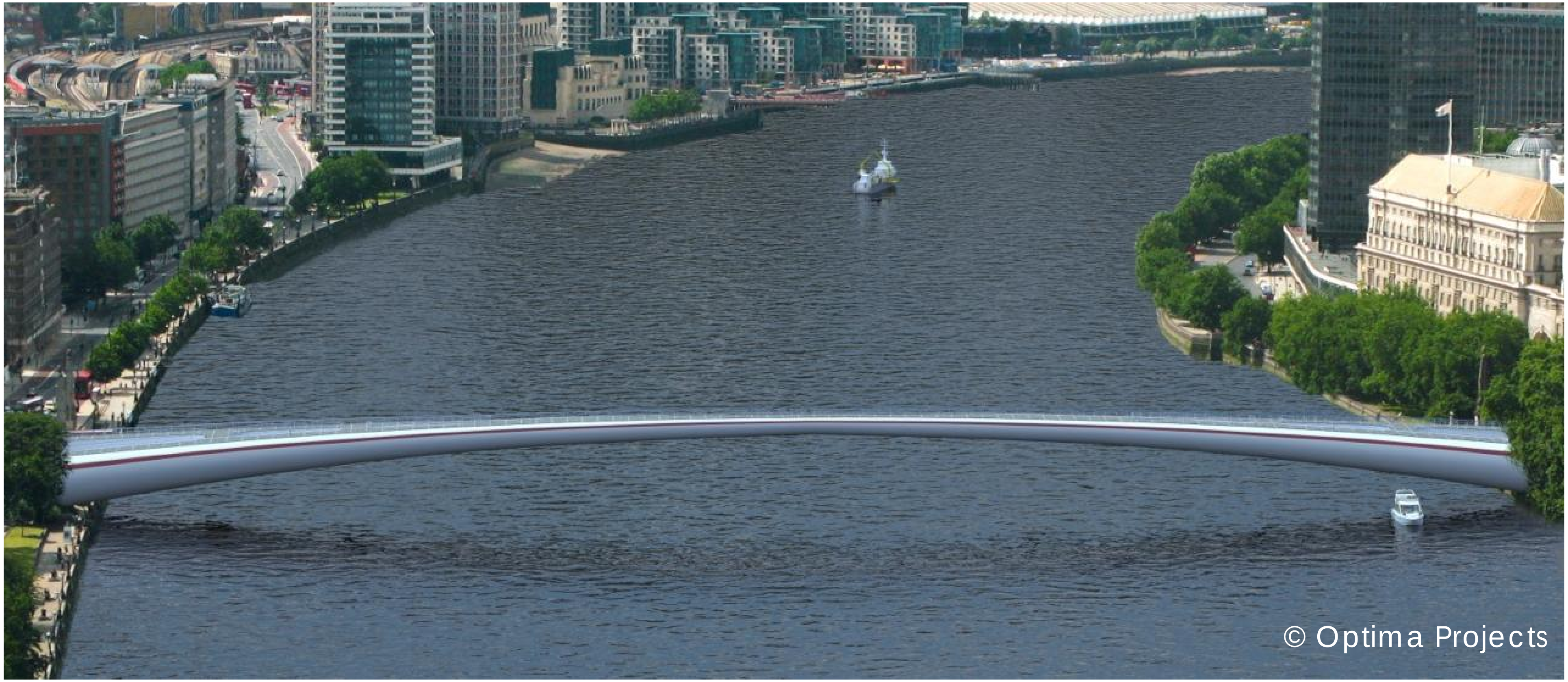
Low laminate stresses
(SLS driven design)

Future opportunities

FRP Composites in bridge design

Bridge applications

FRP Composites in bridge design



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FRP Composites in bridge design

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FRP Composites in bridge design

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FRP composites in bridge design

Bridge Owners' Forum 29 Jan 2013

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