Design of Steel-Concrete Composite Bridges for Rapid Disassembly, Repair or Replacement: Smart Structural Details, Full-Scale Tests, and Design Rules

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Outline

• Resilience (short-term vs long-term stressors)

  • Steel-concrete composite bridges and the need for resilience against long-term stressors

  • The LNSC shear connector

• Experimental program

• Results

• Conclusions
Structure under short-term stressors

- $t_0$: time of occurrence of strong earthquake, hurricane, tsunami
- Difficult-to-repair damage
- Long repair time
- Disruption to services and occupation
- High socio-economic losses
Resilient vs non-resilient structures under short-term stressors

Non-resilient structure - repair time is long

Resilient structure – repair time is short
Structure under long-term stressors

- $t_0$: time of detection of damage (inspection or structural health monitoring program)
Resilient vs non-resilient structures under long-term stressors

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Resilient structure – repair time is short
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Steel-concrete composite bridges

**Well-known advantages**

- Superior stiffness/strength
- Speedy installation
- Economy
Steel-concrete composite bridges

- Increases in traffic flow
- Increases in the allowable weight of vehicles compared to those considered in the initial design
- Use of de-icing salts (especially in regions of cold climates)
- Poor quality of construction materials
- Low maintenance

- One third of the 607,380 bridges in the USA are in need of maintenance (ASCE 2013)
- Deterioration is an important issue for bridges in Europe (PANTURA 2011)

- Decks are typically deteriorating faster than other bridge components
- The decks of 33% of the bridges in the USA are in need of repair/replacement after an average service life of 40 years (ASCE 2013)
- Replacement of the deck is the typical maintenance decision because repair methods do not ensure adequate extension of the bridge lifespan (Deck et al. 2016)
Steel concrete-composite bridges under long-term stressors

- Monolithic connection (welded studs embedded within the concrete slab)
- Repair or replacement of a deteriorating deck or other component is a costly and time-consuming process due to the monolithic connection between the steel beam and the concrete slab
- Long traffic interruption and associated socio-economic losses
We need a step change in our bridge design philosophy to ensure resilience against long-term stressors

- Extension of the bridge *lifespan* shall become a major design goal

- A possible way is to develop bridges that allow disassembly without compromising structural performance and integrity

- Disassembly offers the unique advantage of easy replacement of deteriorating structural components (e.g. deck of steel-concrete composite bridges) with *minimum disturbance* to traffic flow

- This of particular importance as demands on bridges will increase dramatically in the future due to *urbanisation* and *climate change*
Resilience in steel concrete-composite bridges

Resilience in precast steel-concrete composite bridges through design for disassembly and rapid repair or replacement

• Calls for a demountable shear connector that will allow rapid and easy separation of the slab from the beam

Resilient bridge – repair time is short
Research goal

Develop a demountable shear connector without compromising structural performance!
Previous developments (non-embedded in the slab)

- Construction tolerances
- Gaps in the steel beam – precast slab interfaces may prevent adequate bolt fastening and cause slab cracking
- Slip of the bolt
- Large shear strength and slip capacity
- Slab and shear connector are removable
Previous developments (embedded in the slab)

- Lower initial stiffness
- Lower strength (at 6 mm slip)
- Shear connector is fully embedded in the slab (slab is removable, shear connector is non-removable)

Lam and Saveri (2012)
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Locking-Nut Shear Connector (LNSC) - Main components

- Nut
- Plate washer
- Plug
- Grout
- Bolt
- Conical nut
- Nut 1
- Nut 2
- Nut 3
- Steel beam

Dimensions:
- 600 mm
- 10 mm

Bolt threads
Construction step 1

- A pair of high strength steel bolts are fasten at the upper beam flange

- Bolting is achieved with a carefully designed double nut configuration

- The bolt hole has a chamfered finish at the upper surface following a 60-degree angle to form a countersunk seat

- The upper nut has a conical shape to fit in the countersunk seat

- The lower nut is fasten (**bolt is locked in the steel flange**) to prevent bolt slip

- The beam is transferred to the site
Construction step 2

- The slab is prefabricated with tapered holes following a 5-degree inclination to form an inverted conical oval shape

- Precast planks are transferred to the site and positioned on the top of the beam

- Each pair of bolts coincides approximately with the center of a slab hole (no construction tolerance issues)
Construction step 3

- Two inverted conical precast concrete units (plugs), identical in inclination with the slab pockets, are positioned in the slab pocket.

- Each plug has a central circular hole to accommodate a bolt (no construction tolerance issues).

- Cement grout is used to fill the gaps between the bolts and the plugs, and, the gaps between the plugs and the slab.

- Nut on the top of the plugs is tightened to hold the plugs down before grout hardening.

*Construction does not involve working underneath the bridge deck!*
Disassembly (method 1)

- Unfasten lower nuts
- Slab and shear connectors can be uplifted as a whole
Disassembly (method 2)

(a) Extension bolts
M16 Coupler nuts
Removed original nuts
Upper face of slab

(b) Timber blocks

(c) M16 nuts
Spreader steel beams

(d) Extracted Pocket
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Standard pushout test per Eurocode 4
<table>
<thead>
<tr>
<th>Test No.</th>
<th>8.8 Bolt Dia. (mm)</th>
<th>Bolt preloads (kN)</th>
<th>Slabs (mean)</th>
<th>Plugs (mean)</th>
<th>Grout (mean)</th>
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<td>Nuts 1–2*</td>
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</table>
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Three identical tests - 8.8 M16 bolts

- Negligible scatter in the load – slip behaviour
- Superior strength (characteristic value equal to 171 kN!)
- Superior slip displacement capacity (more than 12 mm!)
- No slip of the bolt

<table>
<thead>
<tr>
<th>Test number</th>
<th>Ultimate load (kN)</th>
<th>Slip capacity (mm)</th>
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<td>Average</td>
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<td>Standard deviation</td>
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<td>Error (%)</td>
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</table>
Variation in structural behaviour (LNSC vs Welded studs)

Superior stiffness

- Superior stiffness, i.e. 100 kN/mm for an M16 bolt
- A modest friction resistance exists. Its value is 12 kN, i.e. 5% of the total shear resistance

Behaviour up to 1 mm and shear force equal to 100 kN, i.e. 50% of the shear resistance
How the LNSC achieves its high stiffness, strength, slip capacity, and low variability in the shear load – slip displacement behaviour?

- Use of high strength (Grade 8.8 in the tests) bolts
- Use of high-strength concrete for the plugs (no need for a high strength concrete slab!)
- High-strength concrete plugs are under nearly triaxial stress confinement conditions – they can develop significantly higher compressive stresses than their design strength
- The LNSC fails always due to fracture in the bolts and not due to concrete crushing (concrete is under confinement conditions!)
- The LNSC ensures that shear failure in the bolts takes place in their un-threaded length (threads are hidden in the conical nut!)
- Smooth flow-able grout around the bolts without variation in voids and aggregates
Resistance against slab uplift

At load equal to 80% of the shear resistance, the slab uplift is only 4% of the corresponding slip displacement!
Effect of bolt diameter

![Graph showing load (kN/bolt) vs. slip (mm) for different bolt diameters. D12 mm (Test 7), D14 mm (Test 8), and D16 mm (Test 12).]
Effect of plug concrete strength

![Graph showing the effect of plug concrete strength](image-url)
Estimation of shear resistance

<table>
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<tr>
<th>Test number</th>
<th>Bolt diameter (mm)</th>
<th>Plug strength (MPa)</th>
<th>Ultimate load (kN)</th>
<th>Eq. (4) (kN)</th>
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</tbody>
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\[ P = \frac{\pi d^2 f_u}{4} \left[ \frac{0.8}{\cos \beta} + 0.4(\sin \beta + \mu \cos \beta) \right] \]
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Conclusions

• Accelerated bridge construction by promoting prefabrication

• Rapid bridge disassembly, repair and replacement (reduction of socio-economic losses associated with bridge maintenance)

• Failure always due to fracture of a high-strength steel bolt (concrete never fails!)

• Superior shear resistance and stiffness (characteristic values for 8.8 M16 bolt are 172 kN and 100 kN/mm, respectively)

• Superior slip capacity (up to 14 mm)

• Significant stiffness/resistance against slab uplift (less than 4% of the corresponding slip displacement at shear load equal to 80% of the shear resistance)
Recently completed (10 m beam test)
Future research (funded)

• Fatigue evaluation

• Development of FEM models
Acknowledgements

- Engineering and Physical Sciences Research Council of the UK (Impact Acceleration Fund)
- Iraqi Ministry of Higher Education and Scientific Research (PhD scholarship)
- Horizon2020 MSCA IF Fellowship
Details on the LNSC


Future publications and related research

https://www.southampton.ac.uk/engineering/about/staff/tk4g16.page

Thank you for your attention!