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Strut-and-tie models for deteriorated reinforced concrete half-joints

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ABSTRACT

A reinforced concrete half-joint bridge consists of suspended span dapped-end beams or a full-width deck supported on the nibs of abutments or adjacent beams. The design of their disturbed regions is traditionally performed by means of strut-and-tie modelling. The design provisions found in standards and codes can be used for the assessment of existing structures with minor adjustments. However, current documents provide limited guidance on the incorporation of deterioration aspects such as corrosion, insufficient anchorage lengths, and crack formation.

Experiments performed on 12 half-joint beams demonstrated the effects of single defects, but synergistic effects were also found to exist and might lead to much higher reductions than expected from the sum of individual defects. These results were compared to different strut-and-tie models (STMs) and the application of STMs to achieve the highest lower bound estimate of the load carrying capacity is discussed.

For the beams studied in the current work, the predictions based on codes and standards, combined with appropriate methods to incorporate deterioration effects, led to safe load bearing capacity estimates. However, the developed STMs seem to be, in some instances, unable to pick up alternative load paths that develop as soon as the capacity of a certain tie is reached. Hence the actual capacities might be higher than what is obtained from the STM calculations.

1. Introduction

With increasing traffic volumes and load demands in an era of limited resources, there is a pressing need for the accurate strength assessment of aging infrastructure. When assessing the load carrying capacity of existing bridges, the influence of factors including deterioration and previous repair works are often disregarded since current code provisions or guidelines do not provide sufficient guidance. However, the de la Concorde Overpass collapse in 2006 [1], killing 5 people, emphasises the importance of proper inspections, maintenance, and adequate assessment techniques.

Reinforced concrete half-joints, such as de la Concorde Overpass, provide specific challenges with respect to their assessment. A half-joint bridge consists of suspended span dapped-end beams or a full-width deck supported on the nibs of abutments or adjacent beams (Fig. 1). Advantages of this type of bridge detailing are the suitability for precast construction [2] and a reduced construction depth with a level running surface along the bridge deck and the support spans. Disadvantages are the vulnerability of the structures to deterioration at the nib due to seepage of chloride-rich water through the expansion joints and the existence of large regions that are not easily accessible for inspection or repair.

Common issues raised during half-joint bridge assessments are [3]:

- Deterioration of the concrete and/or reinforcement
- Inconsistencies between the as-built and as-designed internal steel reinforcement
- Non-compliance of half-joints with current code provisions

Deterioration processes, such as carbonation, chloride ingress, and freeze-thaw cycles, mean that the mechanical properties of the concrete and steel will alter over the lifetime of a reinforced concrete half-joint. The extent to which these processes affect the compressive strength, tensile strength and modulus of elasticity of the concrete can be significant [4].

During the design process, the reinforcement detailing can be carefully considered and specified, but in practice, the execution might prove to be difficult due to dense reinforcement cages or a lack of accessibility to certain regions within a specific half-joint geometry. These alterations might have a significant impact on the load carrying capacity of a structure and inconsistencies should be carefully analysed during the assessment. The misplacement of some of the reinforcing

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Nomenclature

Abbreviations and notations

α	residual bond factor (range of 0.15–0.40) [–]
α_s	angle between compressive strut and adjoining tension tie [–]
α_{cr}	bond reduction factor [–]
β	bar type coefficient (0.70 in case of deformed bars in tension) [–]
ε_s	tensile strain in concrete in direction of tension tie [–]
γ_{mb}	partial safety factor ranging between 1.25 and 1.4 [–]
λ	ratio of actual to provided bond length [–]
ν	reduction factor [–]
$\sigma_{c,st}$	concrete compressive stress in strut [MPa]
$\sigma_{s,st}$	steel compressive stress in strut reinforcement [MPa]
$\sigma_{s,tie}$	steel tensile stress in tie reinforcement [MPa]
$A_{c,st}$	effective concrete area of the strut [mm^2]
$A_{s,st}$	area of provided compressive reinforcement along strut [mm^2]
$A_{s,tie}$	area of provided tensile reinforcement along tie [mm^2]
A_{tr}	area of transverse reinforcement [mm^2]
D_0	original reinforcing bar diameter [mm]
d_b	reinforcement bar diameter [mm]
d_p	depth of pit corrosion [mm]
e	distance between the bearing plate and the reinforcing bar [mm]
f_{bd}	design bond strength assuming perfect bond conditions [MPa]
$f_{bd,red}$	reduced bond strength [MPa]
f_c'	concrete compressive strength [MPa]
f_{cd}	design concrete compressive strength [MPa]
f_{ck}	characteristic concrete compressive strength [MPa]
$f_{c,u}$	allowable concrete compressive stress [MPa]
f_n	lateral pressure [MPa]
f_s	steel stress at critical section [MPa]
f_y	yield stress of reinforcing steel [MPa]
f_{yd}	design yield stress of reinforcing steel [MPa]
$F_{n,st}$	bar force in a strut [N]
$F_{n,tie}$	bar force in a tie [N]
F_{ult}	ultimate failure load of half-joint [N]
$F_{ult,\ exp}$	experimentally obtained ultimate failure load of half-joint [N]
$F_{ult,\ STM}$	ultimate failure load of half-joint according to STM [N]
l_a	actual provided anchorage length of reinforcing bar [mm]
l_d	anchorage length of reinforcing bar [mm]
STM	strut-and-tie method]
s	spacing of reinforcing bars [mm]
t	depth of the strut [mm]
w	width of the strut [mm]
x_b, x_y	dimension of remaining cross-sectional area after corrosion [mm]
x_c, x_c	dimension of pitting corrosion [mm]

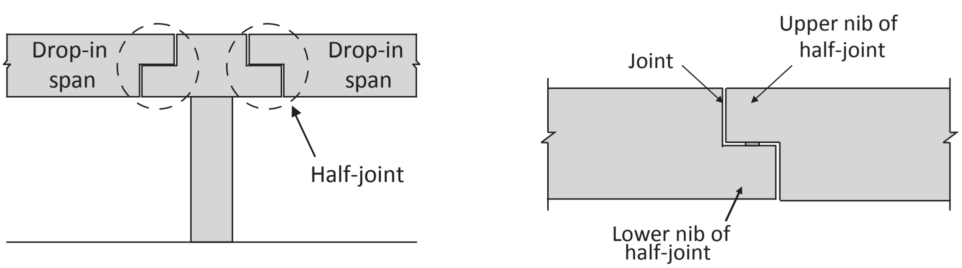

Fig. 1. Half-joint principle for reinforced concrete bridges.

bars was noted in the investigations into the de La Concorde Overpass collapse [5].

Code provisions have changed over the last few decades. Back in the 1960s and 1970s, the shear provisions, for example, were typically less stringent than they are in current codes. In some cases, minimum shear reinforcement ratios were not required [6] and, hence, older half-joints being assessed today might fail the assessment by default as they lack the minimum amount of shear links. Mitchell et al. [7] compared anchorage requirements for half-joints provided by historical and current versions of the PCI Handbook [8]. They concluded that there were cases where the older design guidance underestimated the need for anchorage measures and might provide insufficient protection against shear failure.

Hence, deterioration, inconsistencies and non-compliance with current codes can all create concerns when performing assessments. IAN 53/04 'Concrete Half-Joint Deck Structures' [9] states that assessors should use their engineering judgement to take into account the deteriorated state of the half-joint during capacity checks, including likely reinforcement section loss and any delamination of the concrete cover. BA 39/93 [10] on the 'Assessment of reinforced concrete half-joints' provides a method to evaluate crack widths (in the serviceability limit state) and emphasises the importance of accounting for corrosion effects in the calculations of the ultimate load capacity. In addition, IAN 53/04 specifically mentions the use of strut-and-tie methods (STM) to assess the remaining load carrying capacity of reinforced concrete half-joints. However, no specific guidance is provided on how to account for certain defects detected during inspections. The way in which deterioration and inadequate anchorage conditions should be dealt with remains unknown.

This paper summarizes the basis of the STM for assessment and STM provisions available in selected design codes. An experimental program exploring the impact of reinforcement layout, anchorage and concrete cracking on the structural capacity of half-joints is briefly discussed, after which the accuracy and validity of the current STM provisions are evaluated in the context of the experimental program.

2. Strut-and-tie method

The application of strut-and-tie methods for the assessment of reinforced concrete half-joints, differs from how STMs would be used in the design of new construction. Assessors are no longer able to design and place tensile reinforcement freely, but have to comply with the provided reinforcement layout of the structure under assessment. Other design options, such as the selection of the preferred concrete quality and strength, are also no longer available. Nevertheless, the use of a STM for assessment shows significant similarities to an STM design process. A typical STM design process can be split up into 3 main phases:

- Step 1: Defining the B- and D-regions