19th Australasian Tunnelling Conference – Acosta-Martínez, Stewart and Hudson-Smith (Eds.)
© 2025 Australian Tunnelling Society, ISBN 978-0-85825-002-4

Comparative analysis of crack width calculation methods for tunnel lining design

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ABSTRACT: Crack width assessment is a critical component of the serviceability limit state (SLS) design check for the reinforced concrete tunnel linings, as it impacts the long-term performance and serviceability of the structures throughout the design lives. A comprehensive understanding of crack width design improves the serviceability and durability of concrete structures and reduces both material usage and maintenance cost. Various design approaches documented in Codes and Standards regarding flexural crack width calculation and assessment are suggested, depending on the specific project requirements. In this paper, three principal methods outlined in Australian Bridge Design Code, Australian Standard for Concrete Structures and Eurocode 2 with regards to flexural crack width design are compared. A SLS axial force-bending moment (N-M) interaction diagram is developed in accordance with approaches in the Standards, and the application of N-M interaction diagram for lining design is demonstrated. Additionally, the influence of as-built excess concrete cover is investigated.

1 INTRODUCTION

Crack width calculation is a critical component of the serviceability limit state (SLS) design check for permanent reinforced concrete (RC) lining in tunnels, as it directly impacts the long-term performance and serviceability of tunnel structures throughout their design lives. Compliance with crack width limits and requirements stated in standards and codes (standards hereafter) are conventionally the fundamental design consideration for permanent tunnel reinforced concrete linings. For the majority of underground tunnel design projects in Australia, the crack width limit for the permanent reinforced concrete lining is typically required to be calculated on the basis of the relevant Australian Standards (AS), and incorporating standards of other countries based on the specific project requirements, including the widely used European Standard, Eurocode 2: Design of Concrete Structures (EN 1992-1-1).

For the design of reinforced concrete, numerous factors influence the crack width design, including steel reinforcement diameter, concrete compressive strength, concrete durability cover, bond characteristics and reinforcement quantity, orientation and distribution across and near the potential crack. However, flexural crack width calculation essentially correlates crack spacing and strain differences between steel reinforcement and concrete strains. The flexural crack width estimation is mainly influenced by the crack spacing parameter.

Australian Bridge Design Code (AS 5100.5), Australian Standard for Concrete Structures (AS 3600) and Eurocode 2 (EN 1992-1-1) are the widely used standards in Australian tunnel projects for SLS crack width design of reinforced concrete structures. The approaches regarding crack width design in reinforced concrete structure design using these standards and the associated similarities and differences amongst the standards are investigated in the sections below.

The essential and principal crack width formulation in these standards is based on Formula 1.

$$\omega = S\ (\varepsilon_{sm} - \varepsilon_{cm}) \quad (1)$$

where, ω is the crack width; S is the maximum spacing between cracks; and ε_{sm} and ε_{cm} are the mean steel and concrete strains over length or spacing between cracks, respectively.

For crack control of reinforced concrete, a minimum area of reinforcement, $A_{s.min}$ is typically required in standards.

In this paper, the SLS axial force-bending moment (N-M) interaction diagram has been developed according to Australian Standards and Eurocode 2 for crack width calculations, and comparisons between envelopes using various design parameters, conditions and considerations are provided.

2 SERVICEABILITY LIMIT STATES AXIAL FORCE-BENDING MOMENT INTERACTION DIAGRAM WITH SPECIFIED CRACK WIDTH LIMIT

Tunnel linings are predominantly flexural-compression structural members (rather than pure flexural members), and the beneficial effects of the compression force must be considered for efficient design. The paper considers the influence of the axial force on the crack width limit design.

Figure 1 illustrates the reinforced concrete SLS axial force-bending moment limit envelope, known as the RC SLS N-M interaction diagram, for the reinforced concrete section defined in Figure 2, with the short- or long-term crack width limited to 0.2 mm, 0.3 mm and 0.4 mm, and uncracked condition. These values are commonly documented in Australian standards and Eurocode for varying structure environmental exposure categories and are discussed in Section 3. Moreover, the maximum concrete compressive stress in the SLS is limited to 0.6 f_c' according to EN 1992-1-1, Clause 7.2 in Figure 1, where f_c' is the characteristic concrete compressive strength.

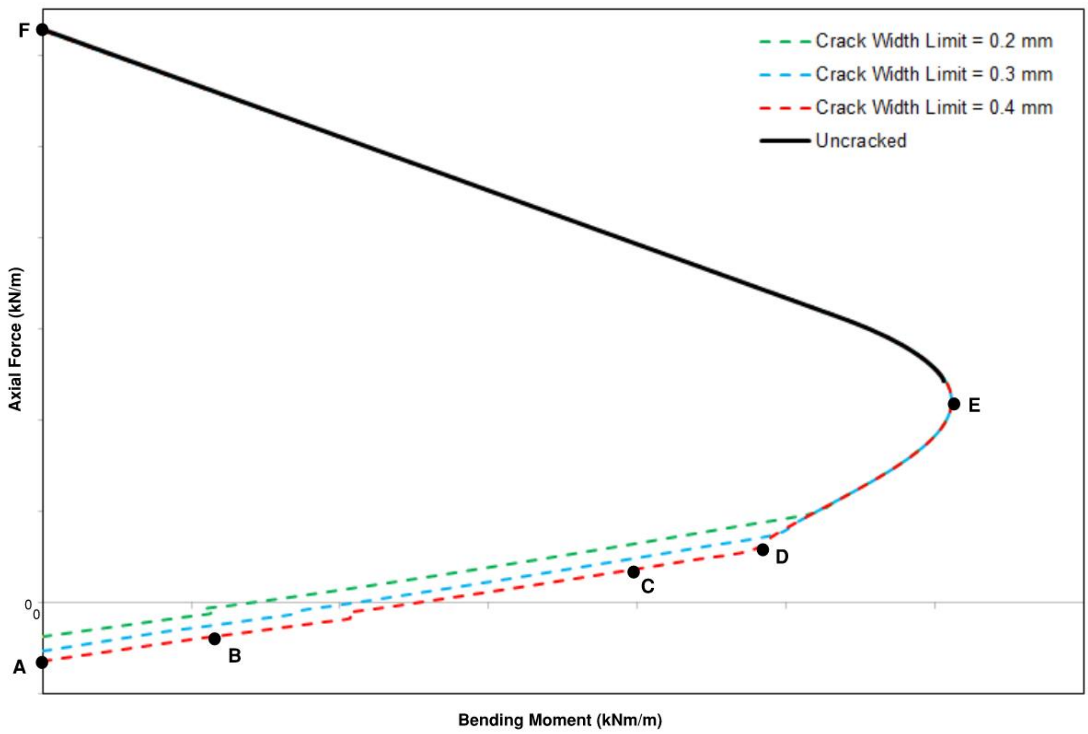
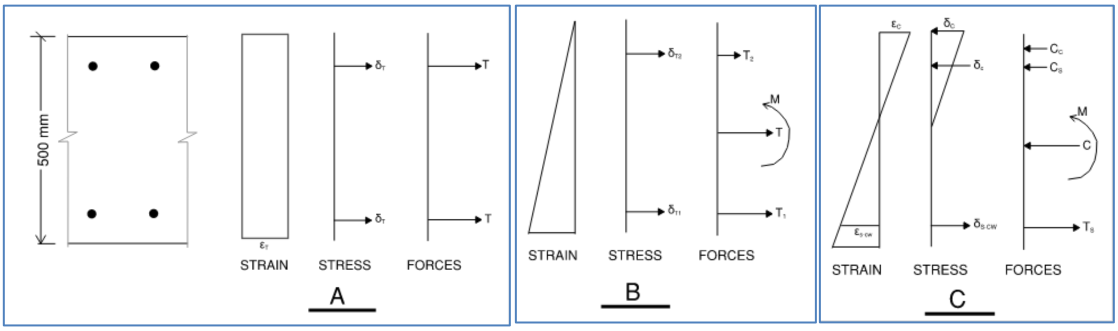
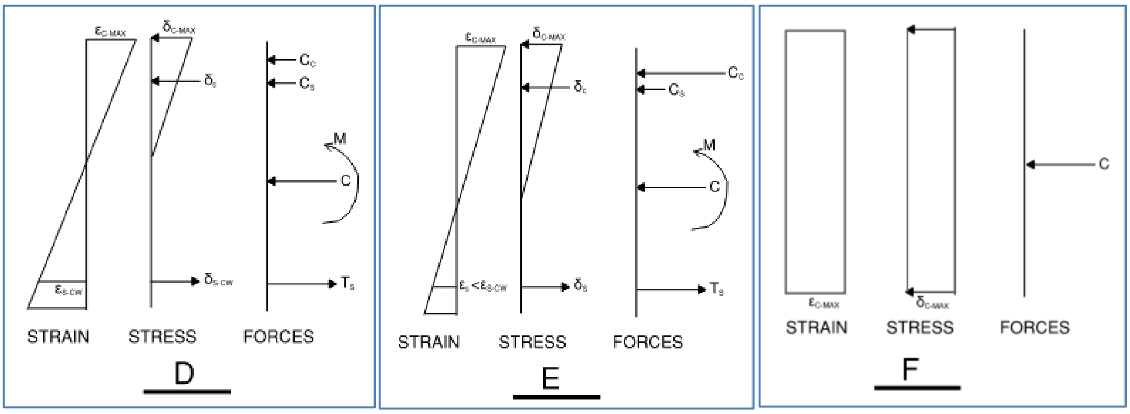


Figure 1. Cracked reinforced concrete N-M interaction diagram with crack width limits of 0.2, 0.3 and 0.4 mm, and uncracked condition.

The SLS N-M limit diagram shown in Figure 1 represents the cracked and uncracked reinforced concrete section behavior under the SLS design limits, namely limited by the maximum concrete compressive stress and the maximum steel tensile stress corresponding to the specified crack width limit.



(a) Point A: Pure axial tension condition; Point B: Transition from pure tension to flexural tension condition; and Point C: Flexural compression condition.



(b) Point D: Balanced condition; Point E: Maximum bending moment under axial compression condition; and Point F: Pure compression condition.

Figure 2. Stress-strain diagrams under various types of design behaviors (a) and (b) of RC section.

The SLS N-M interaction envelope is defined by points A to F.

– Point A represents the pure tension condition, which is governed by the steel stress associated with the specified crack width limit under the design condition of pure axial tension.

– Point B corresponds to the condition where the neutral axis is located at the top of the section. It is the transition between the types of reinforced concrete design behavior from pure tension to flexural tension, as defined in AS 5100.5, Clause 8.6.1. A linear transition is assumed between points A and B in accordance with relevant standards.

– Point C is an intermediate condition between B and D, where the concrete compressive stress remains below the SLS limit, and the steel tensile stress meets the limit for the specified crack width.

– Point D is the balanced condition, where the neutral axis depth results in both the concrete reaching its SLS compressive stress limit and the reinforcement reaching the steel stress limit associated with the specified crack width. This point also marks the transition from primarily flexural to compressive behavior.

– Point E represents the condition with maximum bending moment for the section under axial compression. Here, the neutral axis is located below the balanced condition depth, the concrete compressive stress is at the SLS limit and the steel stress is less than the stress associated with the crack width limit. The increase in bending moment from point C to point E is attributed to the eccentricity of the increasing axial compression force.

– Point F represents the pure compression condition, governed solely by the compressive stress limit for the reinforced concrete.

The SLS limit envelope between points A and D is generally governed by the steel tensile stress limit. The envelope between points D and F is generally governed by concrete compressive stress limit. The sudden change in the SLS N-M interaction envelope between points B and C is due to the transition of the neutral axis across the top reinforcement shown in Figure 2, which changes the function of the reinforcement from tension to compression bars; consequently, there is a notable reduction in the bending moment limit.

For crack width design calculation, AS 5100.5 prescribes a fixed steel stress approach. However, both AS 3600 and EN 1992-1-1 do not prescribe a fixed steel stress limit across the entire interaction envelope for direct crack width calculation. Instead, steel stress varies to comply with the design crack width criteria to calculate the points defining the interaction envelope. Three interdependent variables in the strain diagram for the reinforced concrete section are required to be simultaneously resolved, which involves iterative calculations. These parameters are (1) the concrete compressive stress and strain, (2) the depth of the neutral axis and (3) the steel stress and strain corresponding to the specified crack width limit. As a result, AS 3600 and Eurocode 2 standards require iteration processes to determine the limit envelope between points B and D.

3 FLEXURAL CRACK WIDTH APPROACHES IN DESIGN STANDARDS

The three fundamental and commonly applicable standards in Australian underground tunnel projects are Australian Bridge Design Code, AS 5100.5; Australian Standard for Concrete Structures, AS 3600; and European Standard, Eurocode 2: Design of Concrete Structures, EN 1992-1-1. This section interprets the approaches regarding crack width design in reinforced concrete structure design.

3.1 *Flexural crack width approach in Australian Bridge Design Code, AS 5100.5*

In AS 5100.5, Clause 8.6 and Clause 9.4, no crack width formulations or calculation methods are suggested. However, from Clause 8.6.1(c) it requires two load effect cases to be considered and assessed for the purpose of crack control in reinforced concrete structure design, including SLS load combinations (Case I) and SLS permanent effects for structures within the exposure environment classifications B2, C1, C2 and U (Case II), where exposure classifications are defined in Clause 4.3.

3.2 *Flexural crack width approach in Australian Standard for Concrete Structures, AS 3600*

The crack width formulation given in AS 3600, Clause 8.6.2.3, is the same as Formula 1 and is applicable to both beam and slab design. Moreover, AS 3600 Supplement 1 Clause C8.6.2.3 states that the calculation of crack width in AS 3600 is a modified version of the design calculation approach and procedure documented in EN 1992-1-1. The influence of shrinkage and creep in reinforced concrete is recommended in AS 3600 and in the N-M interaction diagram for the crack width design.

3.3 *Flexural crack width approach in European Standard, Eurocode 2: Design of Concrete Structures, EN 1992-1-1*

In accordance with EN 1992-1-1, Clause 2.3.2.2, the significant impact of shrinkage and creep shall be taken into account for verification in SLS design and only considered at ultimate limit states (ULS) design while age-related effects are significant. The crack width formula given in EN 1992-1-1, Clause 7.3.4 is the same as Formula 1.

4 COMPARISONS OF DESIGN STANDARDS FLEXURAL CRACK WIDTH APPROACHES FOR TUNNEL LINING DESIGN

A case study has been conducted and is discussed in this section with regards to typical underground tunnel permanent linings in Australia and the application of the SLS reinforced concrete N-M interaction diagram to the lining design.

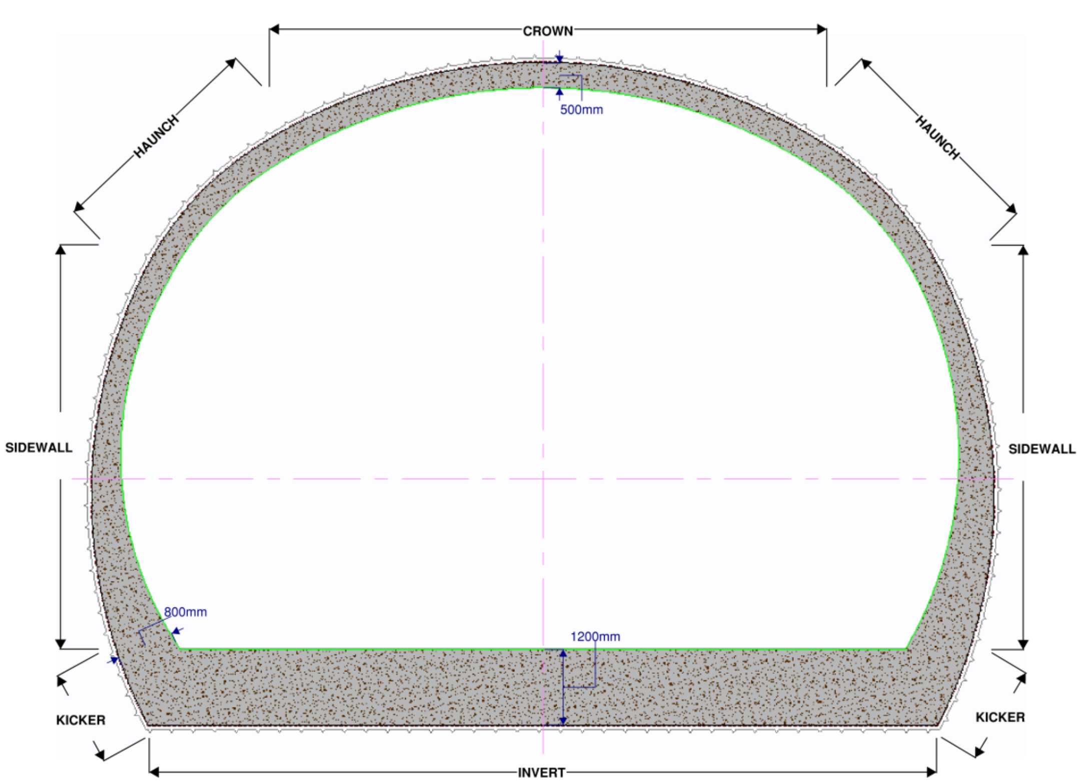


Figure 3. Typical permanent lining nomenclature with indicative thicknesses for 16.0 m wide by 11.5 m high cross-section.

Figure 3 illustrates a typical underground tunnel profile. The representative profile includes the following components–crown (roof slab), haunches, sidewalls, kickers and invert (base slab)– where the thicknesses are assumed as 500 mm, 800 mm and 1,200 mm, respectively, as indicated in Figure 3. In this study, the characteristic compressive concrete strength (f'_c) is 40 MPa. In this tunnel lining design instance, the crack width requirement of reinforced concrete sections under the SLS design is 0.3 mm, with 50 mm of durability concrete cover, and the concrete compressive stress limit is 0.6 f_c', which is 24 MPa.

Per AS 5100.5, AS 3600 and EN 1992-1-1, four SLS N-M interaction envelopes were developed for the 800 mm thick reinforced concrete kicker section in the permanent tunnel lining and are overlain in Figure 4. The AS 5100.5 interaction envelopes were developed for Case I and Case II–details are discussed in Section 3.3. A typical lining SLS compressive force is adopted to determine the bending moment (cracking) limit for the kicker to these standards. The reinforcement arrangements in this tunnel lining example are described in Table 1 and the adopted intrados and extrados bar sizes and spacings are the same.

The crown, kicker and invert sections in the tunnel lining example, with typical reinforcement were evaluated for crack limited bending moment assuming an axial compression force of 1000 kN/m and the results are shown in Table 1. In Figure 4 and Table 1, the AS 3600 N-M limit envelope was developed considering a tunnel lining near the end of its 100-year design life, incorporating time-dependent effects of shrinkage and creep in the calculations. Consequently, the AS 3600 N-M interaction envelope demonstrates the lowest bending moment limit amongst all standards in Figure 4. This is because of the explicit consideration of age-related effects on the crack width calculation.

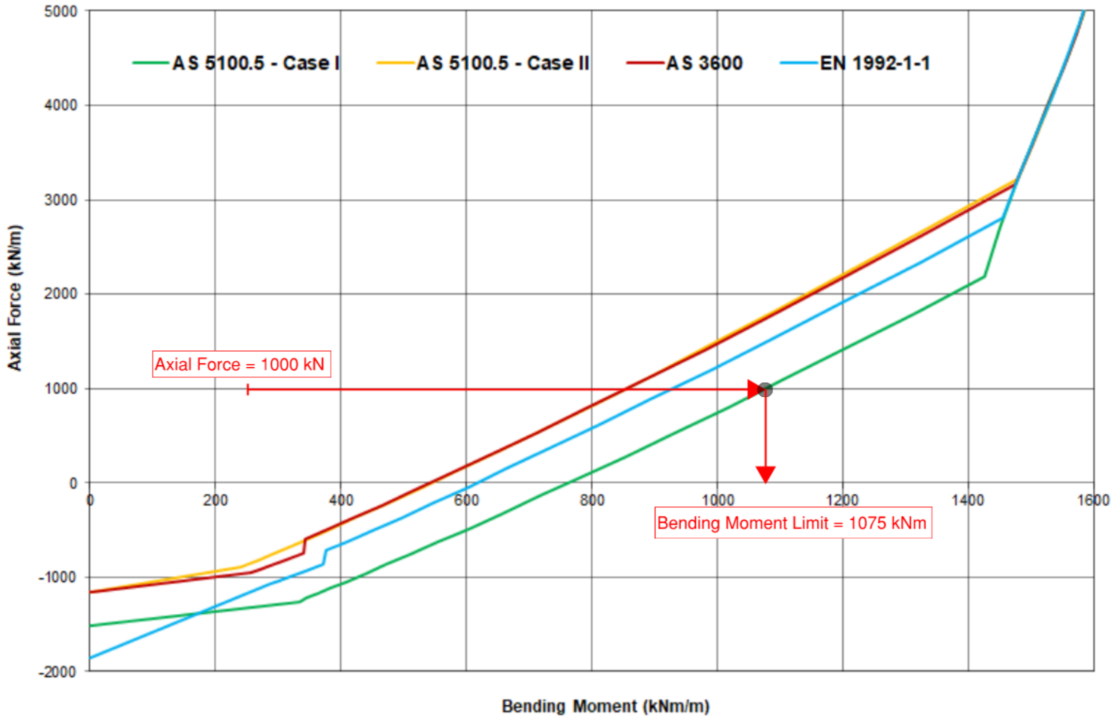


Figure 4. 800 mm thick RC SLS N-M interaction diagram with f_c' of 40 MPa, reinforcement of N28-150 and crack width limit of 0.3 mm.

Table 1. SLS bending moment limit with f_c' of 40 MPa, axial force of 1000 kN, crack width limit of 0.3 mm and durability cover of 50 mm.

Locations	Section Thickness (mm)	Reinforcement[a]	SLS Bending Moment Limit EN 1992-1-1 (kNm)	AS 3600[b] (kNm)	AS 5100.5 Case I[c] (kNm)	Case II[d] (kNm)
Crown, Haunches & Sidewalls	500	N24-150	475	440	516	420
Kickers	800	N28-150	928	851	1075	851
Invert	1200	N32-150	1715	1572	2048	1595

(a) Intrados and extrados reinforcements are identical in each section along the permanent lining. N24-150: Ductility class N steel reinforcement in accordance with AS 5100.5, 24 mm bar, and spacing of 150 mm.
(b) The influence of shrinkage and creep on the N-M interaction diagram of the reinforced concrete crack width design is included in accordance with AS 3600.
(c) Case I: SLS load combinations, from AS 5100.5 Clause 8.6.1(c).
(d) Case II: SLS permanent effects for structure within the exposure classifications of B2, C1, C2 and U, from AS 5100.5 Clause 8.6.1(c).

Moreover, in Figure 4 and Table 1, the N-M interaction envelopes developed on the bases of AS 5100.5 case II and AS 3600 align closely. This indicates that the influences of long-term concrete aging, namely shrinkage and creep are considered in the AS 5100.5 crack width formulation when evaluating the permanent effects in concrete lining response for extreme exposure classes. As presented in Table 1, the variations amongst SLS bending moment limits developed from various standards are significant for the thicker reinforced concrete sections.

5 INFLUENCE OF "EXCESS" COVER IN REINFORCED CONCRETE FLEXURAL CRACK WIDTH DESIGN

Excess concrete cover in the as-built reinforced concrete underground structure, particularly tunnel linings, is common. Excess cover is a relative term and for this discussion is assumed to be a concrete cover to reinforcement greater than required for durability with the highest environmental exposure class plus a positive construction tolerance. As the tunnel linings are predominantly flexural-compression structural members (rather than pure flexural members), the influence of excess concrete cover on the SLS N-M interaction envelope of reinforced concrete structure in the compression zone is investigated in this section. The influence of excess concrete cover in the RC section is demonstrated in Figure 5. The paper considers the influence of the axial force on the crack width limit design. An 800 mm thick RC section with reinforcement of N28-150 or N36-150 is examined to determine the effect of excess cover. In this study, three scenarios of concrete covers are investigated, including zero excess cover, which is the base case and ideal design condition, and 50 mm or 100 mm excess concrete cover, assuming 50mm durability cover and ignoring reinforcement placement tolerances.

The excess cover is considered to be located exclusively on the tensile face of the RC section. The results, when adopting the EN 1992-1-1 formulation and assuming 40 MPa concrete, showed that for a RC section in the regions in the compression zone of the N-M interaction diagram, the increase of concrete cover enhances the magnitude of the SLS bending moment limit at the durability cover depth because of increased section thickness. As the durability-related concrete cover requirement for the structural element has been achieved and exceeded, it is reasonable to consider and calculate what the crack width may be below the concrete surface at durability cover depth from the reinforcement. While the concrete surface crack width may be visible and easily measurable post-construction, the structure design life is generally related to protection of steel bar reinforcement against corrosion and SLS crack widths at durability cover are the primary design approach achieving the intended design life.

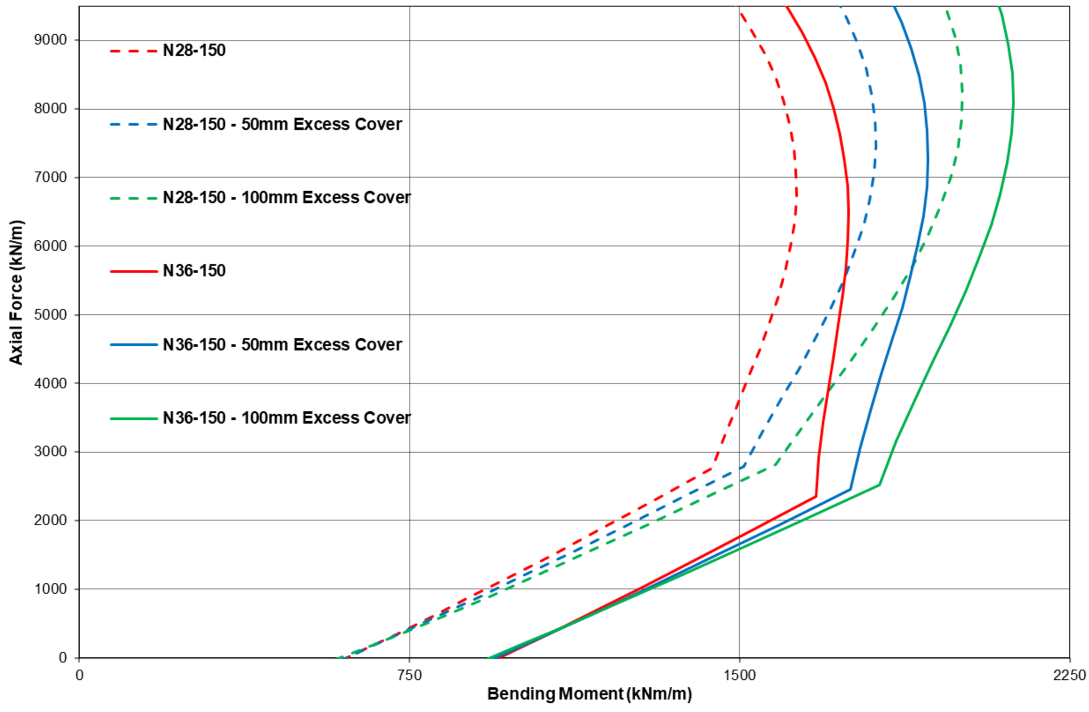


Figure 5. 800 mm thick RC SLS N-M interaction diagram with various excess covers.

6 CONCLUSION

Specific project requirements for permanent lining design for most Australian underground tunnel projects—especially metro tunnel projects—widely adopt the SLS crack width design criteria for reinforced concrete elements. The SLS crack width design typically governs the design.

AS 5100.5, AS 3600 and EN 1992-1-1 are the three essential, and applicable standards adopted for Australian underground tunnel project design. The formulae for calculation of design SLS crack widths in reinforced concrete structures documented in AS 3600 and EN 1992-1-1 adopt the same technical approach. The age-related material effects, shrinkage and creep, to be considered in SLS design according to AS 3600. Their incorporation understandably results in bending moment limit reductions in the N-M interaction diagram compared with the EN 1992-1-1 approach.

In accordance with AS 5100.5, two load effects cases are required in SLS crack width design, namely case I–SLS load combinations and case II–SLS permanent effects.

For the tunnel lining SLS structural design, the critical design cases, with respect to crack width limit, are when the load case combinations result in low axial compression force in the lining. In this scenario, the N-M interaction diagram based on the AS 5100.5 case I approach gives the largest bending moment limit at the adopted crack width compared with the other standards. The AS 5100.5 case II envelope gives similar, but slightly beneficial limits, as the AS 3600 approach envelope which gives the lowest bending moment limit. The limit developed according to EN 1992-1-1 falls near the middle of the three AS limits.

The influence of excess concrete cover, after lining construction, on the bending moment limit associated crack width at durability cover depth in the compression zone was investigated. The study results, with the EN 1992-1-1 approach, demonstrated that the effect of excess cover in concrete section under axial compression force zone, the bending moment limit increases due to increase of section thickness. It is recommended that, in the case of as-built excess concrete cover to reinforcement, design crack widths should be always confirmed at durability cover depth from reinforcement rather than at concrete surface.

ACKNOWLEDGEMENTS

The authors are grateful to Delve Underground for supporting this paper. The authors wish to express deep appreciation and gratitude to our colleague Michael Behrens for his critical suggestions and valuable review.

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