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Performance Analysis of Different Radial Joint Shapes in Segmental Tunnel Lining.

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ABSTRACT: One of the main concerns regarding the performance of radial joints in segmental tunnel lining has not well studied in spite of many researches and experiences. The radial (longitudinal) joint of segmental lining, i.e. the contact joint between segment to segment in a segmental ring, is chosen and designed in the form of either flat or curved shape. From technical and economical points of view, applying design criteria for the most suitable shape of radial joint plays a major role in dimensioning of segmental tunnel lining. This paper deals with the performance analysis of different features of the radial joints to be applied for both RC and SFRC segmental linings. In more details, the design criteria described in this paper mainly focuses on determining bursting and splitting stresses resulted from radial joint action and on evaluating required traditional steel or fiber characteristics to meet ULS requirements. Three distinct calculation methods are suggested to help the design engineer evaluating and choosing the most effective radial joint shape. All advantages and disadvantages of such radial joint shapes are well addressed in this paper.

1 INTRODUCTION

The idea of application of curved radial joint, instead of flat radial joint, in designing segmental tunnel lining could be attributed to the need for the joint optimization in terms of concentration of bearing stresses in concrete segment since it exceeds, in most cases, the allowable bearing compressive strength of concrete in long term state. The definition of radial (longitudinal) joint is presented in Figure 1.

Such a higher rate of bearing stress could be accredited to the reduction of the effective contact area on the radial joint which often takes place for the flat radial joint shape in most shield-tunnel cases in soft ground condition where the combination of the axial force-flexural moment causes a considerable effect of “joint birdsmouthing” often on the radial flat joint.

The invention of double-convex or concave-convex joint helps keeping the radial joint contact width unchanged even after joint rotation and possible joint off-set, considerably reducing, even eliminating the effect of joint birdsmouthing.

Although there have been a number of valuable simplified or complex approaches for design of segmental lining, none of these provides a technical justification to the criteria considered for the design of a suitable shape of radial joint in segment. This gap is more evident referring to the available international design guidelines and codes for segmental tunnel lining (AFTES 1993, ITA 2000, JSCE 2006, BTS 2010, DAUB 2013, ITAtech 2016, ACI 2016).

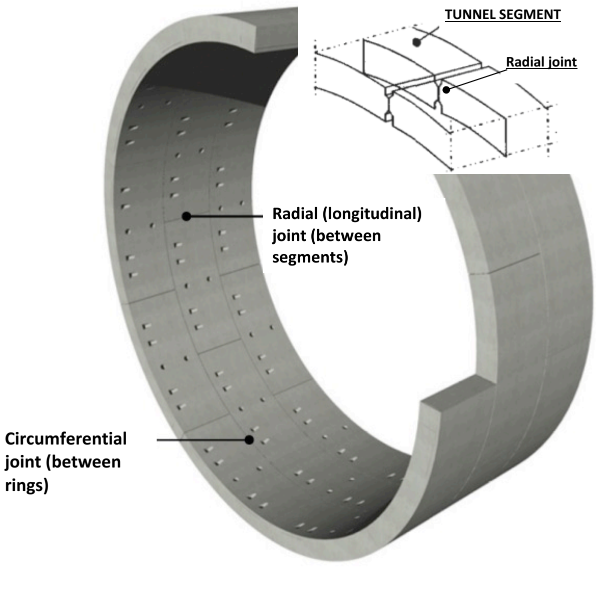


Figure 1. Definition of joints in a segmental tunnel ring.

Hence, it is of paramount importance to the design engineer of the segmental lining, who is liable for dimensioning segmental lining for both geometric and strength-durability aspects, to consider the most suitable shape for radial joint as long as the instructions provided in project design specifications is in agreement.

This paper is, therefore, indented to provide profoundly design engineer with mechanical mechanism of flat and curved radial joints, suggested three design methods, and finally pros and cons of both flat and curved joints. The main message of this paper, from technical point of view, is to help design engineer, considering different design criteria of an individual segmental lining project, being able to choose the most appropriate joint solution, taking into account even the economical aspects.

2 RADIAL JOINT ROTATION

When subjected to the ground and water load, the segmental ring is ovalized (a deformed form of a circular ring being shorter diameter at vertical and longer diameter at horizontal axes). Due to the shape of the rhomboidal and trapezoidal segment shapes the segmental ring ovalization will solely be limited to deformation due to ground loading.

The occurrence radial joint ovalization causes the joint rotation. The joint rotation has a very significant impact on the joint performance in such a way that the rotation gives rise to the geometry eccentricity in addition to the resulting load eccentricities; finally, leading to the birdsmouthing of the joint.

Hence, the design of joint must consider the effect of the eccentricities created in the radial joint due to rotation.

2.1 *Mechanism of radial joint Birdsmouthing*

When a jointed segmental tunnel lining is subjected to the ground/water load, it results in ring ovalization due to deflection / distortion of the ring. Such ring deflection/distortion is manifested at the adjacent segment joints giving rise to radial joint rotation because of presence of load eccentricities at radial joint. The rotation of radial joint in presence of eccentricities can lead to possible joint opening or so-called “joint birdsmouthing”. This phenomenon is likely to take place if the acting bending moment on radial joint exceeds the critical bending moment $M_{critical}$ (the limit in which the joint is fully under compression) obtained by means of middle-third rule (Hearn, 2000):

$$M_{critical} = \frac{N \cdot h}{6} \tag{1}$$

where N and h are the acting normal force and the effective contact length of the radial flat joint, respectively.

The occurrence of birdsmouthing has a very significant impact on the concentration of bearing compressive stress in concrete segment. The greater the joint birdsmouthing, the less the contact joint area, the higher the compressive stress in segment. To reduce the effect of the joint birdsmouthing, the curved joint could be substituted for flat joint.

The simple way for the determination of joint rotation “α” is that of applying simplified geometrical relations (Osgoui et al. 2016), commonly used in design stage. However, the more precise and sophisticated ways are the application of analytical formulations. i.e those of Janβen Joint Model (1983) or to apply a 3D sophisticated numerical model, but the latter it is very complex and time-consuming. Normally the radial joint rotation is described in terms of bending curvature of the section (M-ϕ).

3 FEATURES OF THE RADIAL JOINTS IN SEGMENTS

The ground and water load, which act on segmental lining, is transferred on radial joints between segments. Such loads bring about the tensile stress within segments causing bursting and splitting in both circumferential and transversal directions. The bursting tensile splitting reinforcements should be properly quantified and arranged to act against tensile splitting stresses in circumferential and transversal directions. However, in case of SFRC segments, the replacement of steel rebars are waved in circumferential direction rather they are placed only at transversal direction in the form of lateral chords.

Regardless of type of radial joint shape, the quantity of such reinforcements should be determined such that all necessary structural verifications in ultimate state are satisfied.

Radial joints are either designed as curved or flat. Curved joints are considered in design to overcome the problems of flat joints in specific conditions and to optimize the performance of radial joints.

Although curved joints reduce eccentricity and improve articulation, flat joints sustain a higher load at failure, assuming the flat joints are in full contact (Woods 2003). However with joint rotation the maximum sustainable load for flat joints reduces rapidly while rotation has little impact on the capacity of curved joints.

The resulting rotation causes a change in stress concentration at radial joint reducing the joint contact area at radial flat joint (see Figure 2). Further a joint rotation would cause the lips/steps at radial joint resulting in a considerable reduction of the joint contact width and also influence the centre line of the stress line. On the contrary, the curved joint is to some extent independent of effect of rotation on reducing contact area.

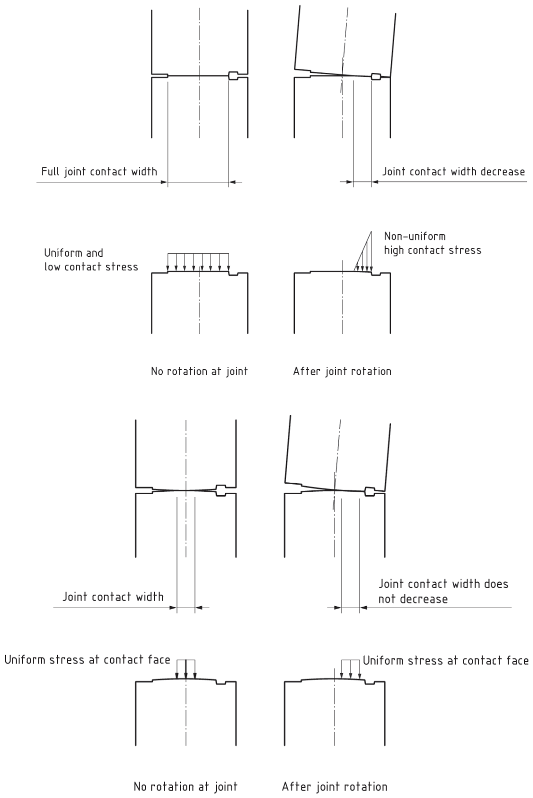


Figure 2. Illustrative sketches for the comparison between radial flat and curved joints in terms of contact width and stress distribution change with joint rotation (PAS 8810. 2016).

3.1 *Radial flat joint*

The radial flat joint is the ordinary shape of joint and it is used for a common joint design. It is also called as block joint. Unless otherwise instructed, this type of radial joint must be considered during geometric design of a segment. This kind of radial joint is often accompanied with guiding rod allowing the segment to be easily guided into its position during the assembly stage and it functions as a shear pin. Moreover, the radial flat joint can be even tightened by means of straight spear or curved steel bolts, even though the latter has not recently been used. A scheme of a typical radial flat joint is shown in Figure 3.

The long-term ground and water loads acting on the segmental lining are transmitted into the segments by means of mainly radial joints and partially circumferential joints (JSCE, 2006; Osgoui & Pescara, 2014). The distribution of such a load on radial flat joint is best described in Figure 4. To calculate the effective and re-assigned contact areas of a radial flat joint, it is essential that the load eccentricities (M/N) be known as given in details in Figure 4.

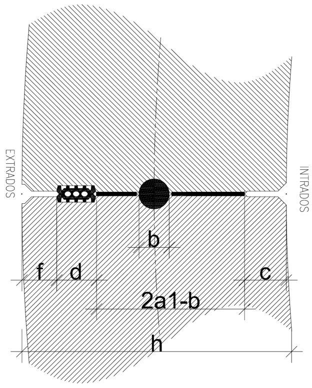


Figure 3. Geometry of a radial flat joint.

Just as the effective contact width is considerably influenced by the amount of the eccentricity, so is the compressive bearing capacity of the flat joint. Hence, in some worse load combinations, the possibility that flat joint shape would not be an applicable solution is high. In this case, the solution of curved joint would be thought. Osgoui *et al.* (2016) have developed a geometric method to calculate the effective joint area associated with the calculated eccentricity as well shown in Figure 4. The suggested geometric solution let determining the intact and redistributed contact areas subjected to axial force (hoop) on radial joint.

A probabilistic calculation has been carried out for different distribution of flat joint shapes, varying dimensions of gasket groove, guiding bar, chamfers, and eccentricity, to evaluate the correlation between concrete bearing capacity and eccentricity.

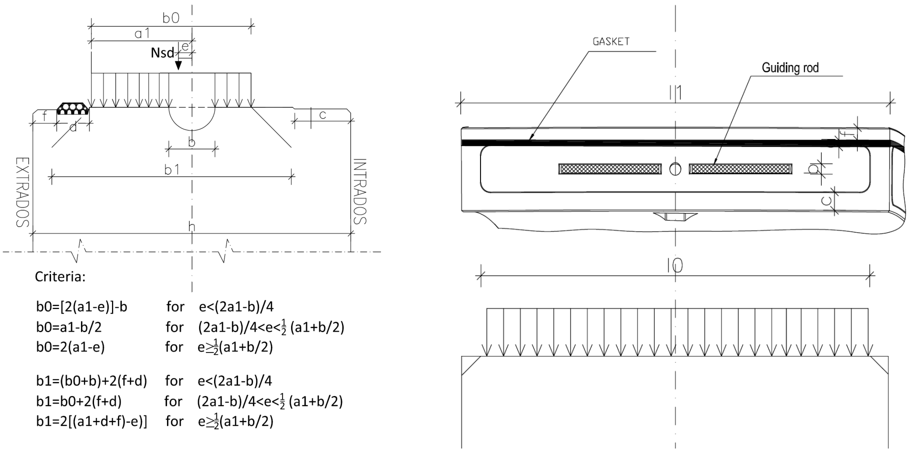


Figure 4. Distribution of load on radial flat joint and the calculation of initially effective and re-assigned contact width and length, considering load eccentricity and geometrical relations to be used in determining the effective contact area of the joint (left: radial direction , right: circumferential direction).

As can be seen from Figure 5, the bearing capacity of the concrete “F_{rdu}” has dramatically been decreased with increasing the eccentricity to such an extent that the acting force “N_{sd}” exceeds the bearing capacity of the concrete, resulting in segment damage. As explained earlier, this case is more likely to happen when the load eccentricity exceeds the critical eccentricity of the section ($h/6$) due to birdsmouthing effect. This is, in fact, the main drawback of the radial flat joint that demand a practically alternative solution to keep the radial joint performance optimized.

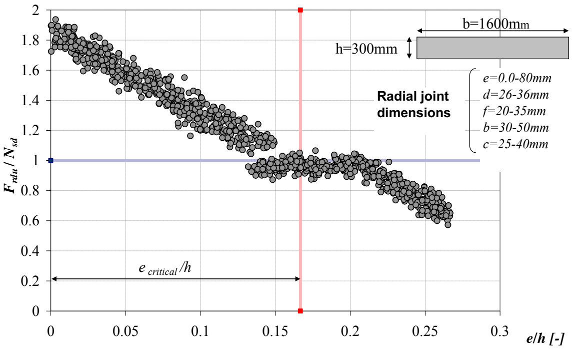


Figure 5 Probabilistic demonstration of the main drawback of the radial flat joint in terms of reduction of bearing capacity with increasing joint eccentricity.

3.2 *Curved joint*

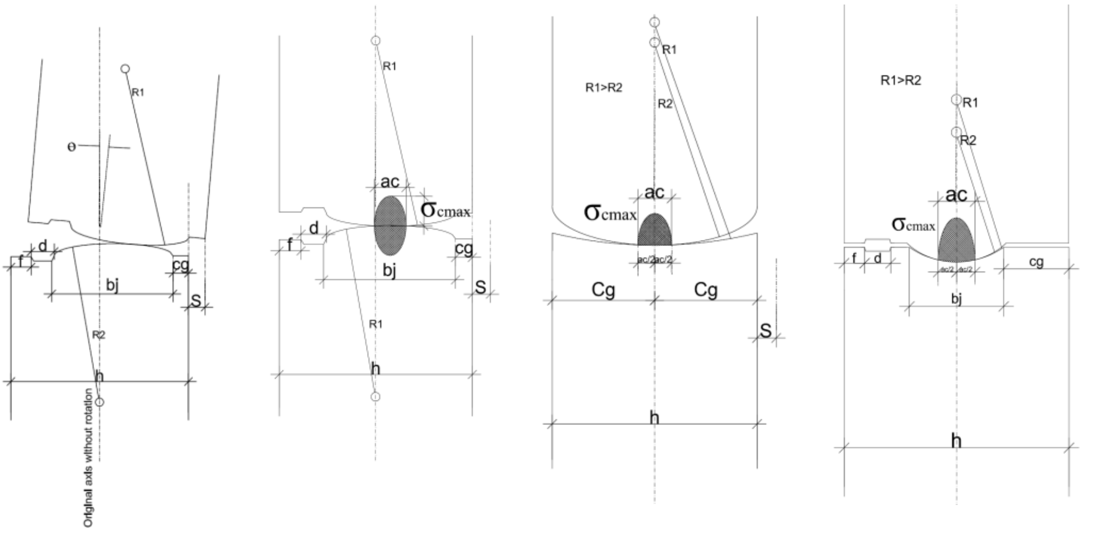
This solution, on the contrary, should be applied when either the project prescription obligates to use such a joint shape or the design engineer acknowledges for such a joint shape, having evaluated the primary results in terms of inducing eccentricity, joint rotation, and the extent of the compressive bearing stress on the radial joint compared with flat joint. The geometries of double-convex and concave-convex joint shapes are shown in Figure 6.

The design of curved joint must consider the effects of stress concentrations created at radial joints. For curved joints the bearing stresses “σ_{cmax}” and joint contact width “a_c” must firstly be calculated.

One of the main advantages of both the convex-convex and concave-convex radial joints is that load is transferred through the middle third of the segment, eliminating stress concentrations on either the intrados or extrados of the segment. Another main advantage is that joint rotation is approximately half of the amount that occurs with a flat joint and the equal joint effective contact area before and after joint rotation, considerably reducing birdsmouthing.

However, the lipping due to effect of rotation is disregarded for the concave-convex pined joint. This special kind of joint should carefully be designed due to very high stress concentration at joint.

The induced compressive stress of the concrete, the width of stress contact between either two convex or concave-convex surfaces are dependent on only elastic properties of the concrete and the radii of the curves. They are simply calculated through the theory of elasticity (Timoshenko & Goodier, 1970):



Double-convex joint Concave-convex joint Concave-convex pined joint

Figure 6. Geometry of curved radial joints, contact length (a_c), and stress concentration zone deduced (σ_{cmax}).

Double-convex $R_1 \neq R_2$

$$a_c = 2\sqrt{\left(\frac{8N}{\pi} \times \frac{R_1 \cdot R_2}{R_1 + R_2} \times \frac{1-\nu^2}{E}\right)} \tag{2}$$

Concave-convex $R_1 > R_2$

$$a_c = 2\sqrt{\left(\frac{8N}{\pi} \times \frac{R_1 \cdot R_2}{R_1 - R_2} \times \frac{1-\nu^2}{E}\right)} \tag{3}$$

where N is the axial (hoop) force on radial joint, R is the radii of curved joints, E is the elastic modulus of the concrete in long-term condition with creep effect (~$E/2$), and ν is the Poisson's ratio of concrete segment. The bearing contact width should then be used to check both compressive bearing and bursting tensile stresses given in follow.

In the next sections, we will show how to calculate the bearing compressive stress and bursting tensile stresses for both radial flat and curved joints which provide us with the performance of joint action.

4 PERFORMANCE ANALYSIS OF CURVED AND FLAT RADIAL JOINTS

The performance of radial joint, flat and curved, is best analyzed in terms of compressive bearing capacity and bursting/splitting stresses induced in segment. Irrespective of shape of the radial joint (flat vs curved), three distinct methods are suggested for the design of the radial joint.

Depending on the desirable reinforcing elements to be used in concrete segment and kind of analysis, one can alternatively choose one of the following simplified methods in design.

4.1 *Calculation method 1*

These calculation methods rely on two separate analyses. The first analysis is to determine the ultimate bearing capacity of the concrete in compression and the second is to calculate the tensile splitting stress by means of one of the practical methods such as analytical approach (based on theory of elasticity, Iyangar 1962 and Leonhardt 1977), numerical models by means of existing suitable software (based on both elastic theorem and plastic analysis in modelling the post-peak behaviour of the concrete after crack propagation).

Nevertheless, during design stage and considering the time limitation, the complexity of the numerical modelling, the usage of the analytical elastic solutions gives also reliable and realistic results. Of course, due to importance of design the use of 3D calculation software is often indispensable.

4.1.1 *Bearing compressive stress due to actions of radial flat joint*

The criteria to be respected in this verification is based on the fact that the compressive force deduced in segment normal to the radial joint axis (N_{sd}) should be lower than that resistant

ULS capacity of the concrete under compression action (F_{rdu}) and ultimate load capacity of the concrete (F_{max}) (EN 1992-1-1:2004), point 6.7 reference to punctual loads:

$$N_{sd} \leq F_{rdu} \leq F_{\max} \tag{4}$$

where

$$N_{sd} = N \times b \times \gamma_f \tag{5}$$

$$F_{rdu} = A_{C0} \times f_{cd} \times \sqrt{\frac{A_{c1}}{A_{c0}}} \tag{6}$$

$$F_{\max} = 3.0 \times f_{cd} \times A_{c0} \tag{7}$$

where N is the normal force acting on radial (longitudinal) joint surface calculated by means of either analytical or numerical methods, b is the width of the segment, and γ_f is the load factor in accordance with the used codes, A_{c0} is the effective contact area of the radial joint, A_{c1} is the re-distributed surface area below radial joint face, and f_{cd} is the long-term design compressive strength of the concrete (EN 1992-1-1:2004).

4.1.2 *Bearing compressive stress due to actions of radial curved joint*

The maximum bearing compressive stress "σ_{cmax}" for radial curved joint is obtained as (Figure 6):

Double-convex $R_1 \neq R_2$

$$\sigma_{c\max} = \sqrt{\left(\frac{N}{2\pi} \times \frac{R_1 + R_2}{R_1 \cdot R_2} \times \frac{E}{1 - \nu^2}\right)} \tag{8}$$

Concave-convex $R_1 > R_2$

$$\sigma_{c\max} = \sqrt{\left(\frac{N}{2\pi} \times \frac{R_1 - R_2}{R_1 \cdot R_2} \times \frac{E}{1 - \nu^2}\right)} \tag{9}$$

And the criterion for verification is:

$$\sigma_{c\max} \leq 2 f_{ck} \tag{10}$$

which is considered as the first structural verification for the curved joint. The Equation 10 is expressed in terms of maximum stress and it is similar to Equation 7 stated in terms of maximum force. In case of problem in this verification, one should increase the class of concrete and/or the segment thickness or switch to flat joint design. However, the latter case is quite unlikely to happen.

4.1.3 *Bursting tensile splitting stresses*

In order to calculate the bursting-tensile splitting stresses resulting from the action of radial joint, the theory of the concentrated force, based on elasticity solution, is used.

The analytical methods developed by Iyengar (1962) and Leonharddt (1977) might alternatively be used to determine the peak transverse tensile stress and the magnitude of the tensile splitting for concentrated forces acting on a prismatic member. These methods are quite quick and precise and are safely applied in preliminary and detail design stages. Nevertheless, thanks to available 2D and 3D structural software that makes it possible to calculate the tensile stresses at radial joints more precisely but rather time-consuming and often difficult to define boundary conditions correctly. However, the results of mentioned method are found to be relatively comparable.

In terms of stress, the bursting tensile splitting stress "σ_y" is suggested to be determined by means of diagrams developed by Iyengar (1962) or Leonharddt (1977). The former is presented in Figure 7.

Having been calculated the bursting tensile splitting force "Z" explicitly by integration of stress (Equation 11) or implicitly by Equation 12, the quantity of the required reinforcements for both circumferential and transversal directions are simply obtained. In this solution, it is assumed not considering any contribution of the concrete in terms of its tensile splitting strength (f_{ctd}) and all tensile splitting capacity should be withstood through tensile splitting capacity of the reinforcements. The bursting tensile splitting force is obtained as:

$$Z = \int^{x=d} \sigma_y \, dx \tag{11}$$

or

$$Z = 0.25 N_{sd} \left(1 - \frac{l_0, b_0}{l_1, b_1}\right) \tag{12}$$

where l_0 and l_1 are the effective contact and re-distributed lengths of the radial joint on circumferential (tangential) direction , respectively while b_0 and b_1 are the effective contact and redistributed widths of the radial joint in transversal (radial) direction (Figure 4).

The tensile splitting reinforcements (traditional steel rebars) provide the total ultimate steel capacity of:

$$F_{st} = A_{st} \cdot f_{yd} \tag{13}$$

where f_{yd} is the design yield strength of the steel reinforcement.

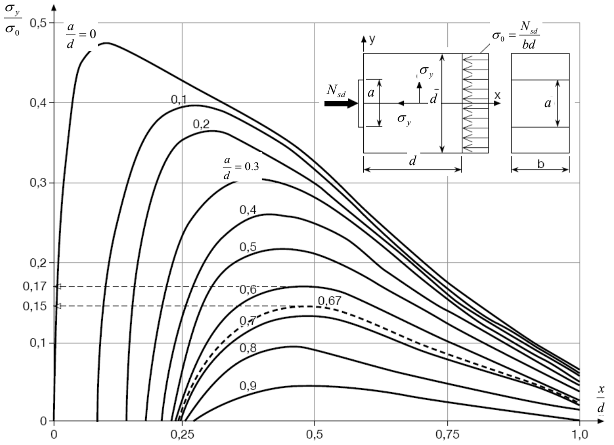


Figure 7. Normograph for the determination of bursting tensile splitting stress (Iyangar 1962)

4.2 *Calculation method 2*

Compared with method 1, this method is based on the concept of pre-stressed concrete end blocks (BS 8110, 1997). The calculation method 2 can alternatively be used for both flat and curved radial joint shapes. This solution allows for the benefit of the tensile strength of the concrete itself in addition to complementary action of reinforcements. Compared with method 1, this method is quite optimistic in design and this concept is also used for SFRC design.

The design is based on a contact width of approximately 0.45 times the thickness of the segment. The basis of this theory is to calculate the ultimate splitting capacity against acting tensile splitting force (ultimate splitting capacity, N_{usc}) taking into account that the tensile splitting is typically the more critical mode of failure for the radial joints (i.e. rather than low-angle shearing):

$$N_{usc0} = \left(\frac{1.9}{\pi}\right) \cdot f_{ctd} \cdot b \cdot h \text{ for plain concrete} \tag{14}$$

where f_{ctd} is the design direct tensile strength of concrete ($f_{ctd}=f_{ctk0.05}/\gamma_c$) ,$h$ is the thickness of the segment, b is the width of the segment.

In case of exceeding calculated eccentricity from the critical eccentricity $0.05h$, the reduced ultimate splitting capacity of the concrete segment should be considered as:

$$N_{usc1} = \left(\frac{3}{4}\right) \cdot f_{ctd} \cdot h \cdot \alpha_{joint} \tag{15}$$

where α_{joint} is the reduction factor for eccentricity > $0.05h$. The criterion for the verification of splitting capacity, therefore, is:

$$N_{usc1} \leq N_{sd} \tag{16}$$

If such verification is not satisfied the radial joint needs to be reinforced by means of traditional steel rebars. In this case the ultimate splitting capacity is calculated as (Swartz *et al.* 2002):

$$N_{ucs2} = 4.45 \cdot f_{ctd} \cdot h \cdot b + 4 \cdot F_{st} \tag{17}$$

$$F_{st} = A_{st} \cdot f_{yd} \tag{18}$$

where b is the width of segment, F_{st} is the ultimate capacity provided by steel rebars, A_{st} is the steel area within a distance from the joint surface equal to 0.8 times the segment thickness.

As can be inferred from Equation 17, contrary to method 1, the ultimate splitting capacity is a function of mutual contribution of both concrete and steels. Based on large-scale tests, Equation 17 has been found to be a lower-bound to ultimate capacities for segments within the reinforcement ratio ($A_{st}f_{yd}$ / A_cf_{ctd}) range of 0.375 to 1.2 (Swartz *et al.*2002).

For tensile splitting, reinforcements should be through-thickness ties that are adequately anchored at each side of the joint, and are located within a distance of about 80-85% of the thickness of the segment from the face of the joint. Finally, the verification of splitting capacity in presence of steel bars is satisfied only if:

$$N_{usc2} \geq N_{sd} \tag{19}$$

If no, the amount of the splitting reinforcement should be incremented so that this criterion is fulfilled. As regards ULS, the splitting reinforcement to sustain the bursting tensile stress is assumed to act at its design strength of $0.87f_{yk}$. However, as for SLS, the same calculation should be done but the reinforcement stress must be limited to 200MPa as also stipulated in some design specifications provided by clients. In this case, as long as the maximum tensile stress exceeds the characteristic tensile strength of the concrete ($f_{ctk,0.05}$), all the transverse splitting forces must be carried by reinforcement (like calculation method 1), remaining the maximum allowable stress of 200MPa.

4.3 *Calculation method 3 suggested for SFRC*

This calculation method is proposed for the SFRC application to evaluate the tensile strength capacity of concrete at radial joint action. The check for the compressive bearing capacity of the concrete at radial joint must followed by means of one of two methods detailed earlier where the plain concrete itself should withstand the acting compressive stresses. However, to evaluate the splitting tensile stress, an integrated analytical method is proposed.

The suggested method relies on the analytical tensile stress formulations studied by Iyengar (1962) or Leonhardt (1976) in combination with *fib* Model Code (2010), which is a superior International Code.

In order to determine the design tensile strength of SFRC, the following relations are used (*fib* Model Code, 2010). Since the radial joint action is associated with the long-term condition, consequently the ULS is to be allowed for by means of simplified rigid-plastic post-peak behaviour model.

$$f_{R3,k} = 0.7 f_{R3} \tag{20}$$

$$f_{Ftu,k} = \frac{f_{R3,k}}{3} \tag{21}$$

$$f_{Ftu,d} = \frac{f_{Ftu,k}}{\gamma_f} \tag{22}$$

$f_{Ftu,k}$ is the characteristic residual flexural tensile strength of the SFRC at CMOD$_3$, $f_{Ftu,k}$ is the design residual flexural tensile strength of the SFRC in ULS, γ_f is partial safety factor, to be considered 1.5, f_{R3} is the residual flexural tensile strength corresponding to CMOD$_3$, obtained by 3-point bending test based on EN 14651, which is calculated as:

$$f_{R3} = \frac{3F_3 l_{sp}}{2bh_{sp}^2} \tag{23}$$

F_3 is the load related to CMOD=CMOD$_3$

l_{sp} is the span length

b is the specimen width

h_{sp} is the distance between the notch tip and the top of the specimen (125mm)

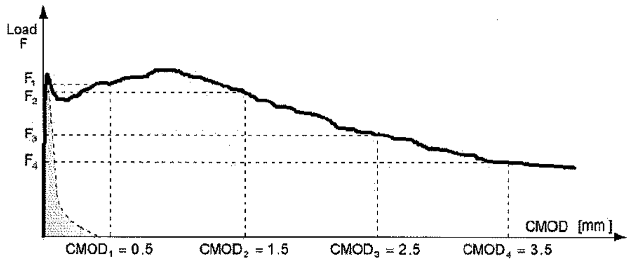


Figure 8. Typical Load F-CMOD curve for SFRC (EN 14651,2003)

Having been determined the design tensile strength of SFRC "$f_{Ftu,d}$", the design check should be carried out as follows:

1. Calculation of maximum tensile stress "σ_y" through applying Iyengar or Leonhardt tensile stress diagram
2. The application of fibre reinforcements is applicable only if both conditions are satisfied as:

$$\sigma_y < f_{ctk,005} \text{ and } \sigma_y < f_{Ftu,d} \tag{24}$$

Otherwise, the splitting tensile steel reinforcements should be replaced in concrete segments. In this case, to estimate the quantity of the steel reinforcements, the relations of method 1 is used, but taking into account the favourable effect of SFRC as:

$$F_{st} = A_s f_{yd} + f_{Ftu,d}\,\omega \cdot b \tag{25}$$

where ω is the distribution depth of the tensile splitting stress and b is the width of the segment.

5 CONCLUSION

Unless otherwise instructed, the preferred radial joint shape for a bolted gasketted segmental lining which sits within a grout annulus is flat. The recent trend in designing radial joint shape is flat. However, some other important design aspects of curved joint should be taken into account.

The results of this study have revealed that the contact length of a curved joint shape is independent from geometrical load eccentricity whereas the contact length of a flat joint decrease considerably due to load eccentricity. Therefore, for a given condition, the ultimate resistance of concrete against bursting force (in compression) for a curved joint is higher than that for a flat joint. However, splitting tensile stresses in concrete of radial joints are higher in curved joints; consequently, a more steel ratio is needed for the curved radial joint configuration. In practice, curved joint may allow for reduced segmental lining thickness, while flat joints, generally, requires a lower steel reinforcement. In contrast to curved joint, the flat joint needs lower strength parameter of steel fibre and lower dosage. Taking into consideration of above-mentioned critical comparison and technical-economical requirements of a given project, a more practical radial joint feature might be chosen.

The key conclusions extracted from this study as regards the critical comparison between the curved and flat radial joints types are well presented in Table 1 that might be used as a practical guideline in defining joint shape.

Table 1. Design comparison between the curved and flat radial joints shapes.

Radial (longitudinal) joint shape	Advantages	Disadvantages
Flat joint	▪ Simple design shape ▪ Best performance in stiff ground with low possible of ring rotation using of full contact joint area ▪ Presence of grove and spring offers a good guidance for the installation and improve the possibility of the transferring transverse forces ▪ Lower rate of splitting reinforcement along radial joint ▪ Recommend application for the ground that cause minor joint rotation and consequent minor eccentricities in resulting solicitations in lining as a consequence of internal forces in segmental lining ▪ Need for lower dosage of steel fibre and lower steel fibre strength class of f_{R3k}/f_{R1k} (*fib* Model Code 2010 classification)	▪ Risk of joint rotation and resulting plasticization of joint ▪ Risk of birdsmouthing due to high possibility of joint rotation ▪ High degree of joint lipping and reducing segment gasket performance ▪ Considerable decrease in joint contact area after joint rotation and occurring eccentricity ▪ Higher bursting stress due to increasing of birdsmouthing and load eccentricities ▪ Risk of insufficient concrete compressive bearing capacity ▪ More risk of segment damage, particularly at corners ▪ Need for higher concrete class in presence of eccentricities
Curved joints (double-convex, concave-convex)	▪ Joint rotation is approximately half of the amount that occurs with a conventional flat joint, considerably reducing birdsmouthing ▪ To some extent independent from load eccentricities ▪ Bending free behaviour for very curved shape (hinge action) ▪ Load transfer through the middle third of the segment, eliminating stress concentrations on either the intrados or extrados ▪ Lower bursting stress due to reduction of birdsmouthing ▪ Constant joint contact area regardless of amount of joint rotation ▪ Applicable in difficult soft soil where the flexural moment rate in lining is high ▪ Possibility in application of lower concrete class ▪ No need for guiding rod ▪ Lip free at concave-convex pined shape	▪ Need for very precise design ▪ Insufficient sealing possibility, but it can be integrated with double-sealing system ▪ Need for higher splitting reinforcement along radial joint ▪ Requiring extremely high tolerances steel moulds for casting the segments ▪ Difficulty in providing segment moulds ▪ Need always for bolt system to connect the adjacent segments in a ring ▪ Often accompanied with double-gasket system at joint ▪ Need for higher dosage of steel fibre and higher steel fibre strength class of f_{R3k}/f_{R1k} (*fib* Model Code 2010 classification) ▪ Satisfactorily results in case of use of old design methods like Muir Wood and Curtis analytical solutions ▪ Difficulty in segment mould preparation and casting ▪ Need for skilful and experienced staff for mould fabrication ▪ Difficulty in ring building

One of the mentioned design methods let engineer analyze the performance of the desired radial joint shape. However, there are significant differences in the results especially in terms of steel ratio given by suggested three methods. In contrast to the method 1, the calculations methods 2 and 3 takes into account the tensile resistance of the concrete. The selection of the most suitable design method is on the responsibility of designer.

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NOMENCLATURE

CMOD=Crack Mount Opening Displacement
RC=Reinforced Concrete
SFRC=Steel Fibre Reinforced Concrete
SLS=Serviceability Limit State
ULS=Ultimate Limit State

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