A hybrid solution proposal for precast tunnel segments

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Abstract
The construction of underground structures is playing a relevant role in modern society. As a result of noticeable tunnel boring machine (TBM) evolution, mechanized excavation methods are gaining increased market shares. TBM driven tunnels are generally used in combination with precast concrete segments as the main support system for reducing or minimizing surface disturbances during construction and to fulfill the project requirements with regards to quality, construction times, budget and safety. Within this framework optimization approaches strongly focused on these process parameters, rather than the general structural performance of the segments. However, improving the performance by using conventional reinforcement, High Performance Fiber Reinforced Concretes (HPFRCs) or a combination of such enables a possible reduction of the lining thickness or the amount of reinforcement. To this aim, this paper presents a new hybrid solution for precast tunnel segments with a reduced thickness, which leads to new perspectives in reducing the total amount of concrete, in decreasing the volume of disposal materials from the boring process as well as to minimize the TBM size. A parametric numerical study is developed for evaluating the effectiveness of proposed hybrid solution. The latter is based on high strength reinforced concrete in combination with HPFRC at the longitudinal joints, whose geometric configuration is properly modified to maximize the segment’s bearing capacity.

KEYWORDS
HPFRC, hybrid segment solution, longitudinal joint, Non-Linear Finite Element Analysis, optimization, precast tunnel segments

1 | INTRODUCTION

The use of underground spaces became more and more important in the past years to improve the mobility of people, goods and for utility purposes (i.e., hydropower, sewage, underground pipelines, power). Several important projects are currently under construction all over the world (i.e., Grand Paris Express, France; Brenner Base...
Tunnel, Italy-Austria\textsuperscript{2}). A considerable increase in tunnel constructions can be accounted to the introduction of mechanized tunneling and the constant evolution of boring machines.\textsuperscript{3} Furthermore, in soft ground, weak rocks or, generally, in complex ground conditions, mechanized tunneling oftentimes is the method of choice.\textsuperscript{4} In this case, the tunnel lining is usually constructed by installing numerous adjacent rings, each composed of several precast concrete segments.\textsuperscript{3,4}

These segments are subjected to a variety of loading scenarios during their production, transportation as well as the boring phase and service life, leading to the following main loading conditions: demolding; primary and secondary storage; transportation; positioning by segment erector; thrust jack forces from the tunnel boring machine (TBM); ring behavior of the tunnel lining embedded in the ground and ring behavior under extreme conditions such as fire, explosion, or earthquake.\textsuperscript{5–7} In order to increase their resistance during these different loading stages and to ensure a ductile material behavior, tunnel segments were traditionally reinforced by conventional steel bars. However, during the last years many efforts have been devoted to develop new reinforcement solutions, generally based on Fiber Reinforced Concretes (FRCs) with or without a possible addition of traditional rebar.\textsuperscript{8–10} These solutions mainly aim to improve the performance of the lining in terms of bearing capacity increase and/or crack control and to speed up the industrial production process.\textsuperscript{6}

Plizzari et al.\textsuperscript{11,12} initially proposed an optimized hybrid reinforcement solution based on steel fiber reinforcement plus two longitudinal chords (along the circumferential joints) composed of conventional curved rebar and stirrups. The interaction of Steel Fiber Reinforced Concrete (SFRC) and curved rebar provides the necessary flexural bearing capacity and remarkably improves the tension stiffening and crack control at the Serviceability Limit State (SLS). Moreover, the curved rebar provides an additional resistance to withstand the high tensile spalling stresses occurring during the TBM thrust phase. More recently, this hybrid reinforcement solution was also extended to polypropylene fibers.\textsuperscript{9} It is worth noting that these approaches primarily focused on improving the lining’s performance by modification of the reinforcement only. They refer to typical lining thicknesses and concrete strength classes. However, the hybridization process can be further advanced to also improve the structural performance in terms of increased bearing capacities, which can be used to reduce lining thicknesses by adopting high strength concretes in combination with other advanced material concepts. In fact, such hybrid solutions can also combine different mechanical property concretes in different regions of the segment, depending on the prevalent stress field.

Among other critical areas of a tunnel segment, the longitudinal joints, where the ring’s axial force is transferred between adjacent segments, are especially prone to structural improvements since they oftentimes govern the segment design. In this regard, a new reinforcement solution for longitudinal joints was proposed by Smarslik and Mark.\textsuperscript{13} It is based on a combination of a High Performance Fiber Reinforced Concrete (HPFRC) layer and reinforcing steel bars in the longitudinal joint contact area derived from numerical topology optimization methods.\textsuperscript{14–16} The tensile splitting stresses occurring at the longitudinal joints are effectively covered by the cooperation of HPFRC and rebar. The advanced reinforcement solution is combined with geometric modifications of the contact area and lead to significant increases of the joint’s bearing capacity with respect to the traditional solution. It was validated experimentally and was found to enable an overall lining thickness reduction.

Within this framework, by adopting the aforementioned local reinforcement solution at the longitudinal joint\textsuperscript{13}, this paper presents a new hybrid solution for the whole lining segment with the main aim of reducing the segment thickness. In fact, this approach offers new perspectives in the reduction of the overall concrete volume in precast tunnel elements as well as in a reduced volume of disposal materials from the boring process. In addition, a possible reduction of the boring machine size is expected as another important advantage. The corresponding conceptual process of tunnel segment evolution, starting from the traditional solution and leading to the high-performance hybrid solution with minimum volume, is schematically depicted in Figure 1. While aiming at keeping the load bearing capacity constant, the lining thickness is reduced to the minimum necessary.

The aforementioned process and the effectiveness of the new hybrid solution is verified through non-linear numerical simulations of the final loading phase (service conditions) since it represents the predominant stage in the service life of a tunnel segment. The non-linear numerical model is validated based on the experimental results of small scale samples presented in Smarslik and Mark.\textsuperscript{13} Furthermore, the numerical simulations serve as a preliminary investigation for the evaluation of a new, more advanced testing device designed to experimentally analyze the behavior of full-scale lining segments under service conditions, which was developed by the authors and is currently providing first results.

## 2 | MATERIALS

Two different concrete strength classes are considered, whose main mechanical properties, according to Eurocode 2,\textsuperscript{17} are reported in Table 1. Class C40/50
corresponds to a concrete strength typically used in tunneling projects, while C70/85 is a high strength concrete chosen to withstand axial compressive stress at a reduced thickness for the hybrid design during final service conditions. Furthermore, a HPFRC is used at the longitudinal joints to cope with the local tensile splitting stresses. It has a characteristic cylindrical compressive strength of 70 MPa and a post-cracking performance class “8c” according to Model Code classification. More details of the HPFRC’s mechanical properties are reported in Table 2. Fracture properties are provided as post-cracking nominal flexural strengths as obtained from previously conducted experimental campaigns. For the HPFRC a cocktail of two different steel fiber types with a total content of 80 kg/m³ (40 + 40 kg/m³) was used. Fibers having a length (Lf) of 13 mm, a diameter (ϕf) of 0.19 mm and an aspect ratio (Lf/ϕf) of 68 (filament strength of 2000 MPa) were combined with fibers having aspect ratio equal to 80 (Lf = 60 mm, ϕf = 0.75 mm, filament strength of 1225 MPa).

Traditional reinforcing steel bars (B500A) are used for the traditional segment. The characteristic tensile yielding strength (fṣyk) and the elasticity modulus (Ee) correspond to the common values of 500 and 200,000 MPa, respectively.

3 | REINFORCEMENT PROPOSAL

Among the different loading conditions for precast tunnel elements, the final stage (in service conditions, when the lining is embedded in the surrounding ground) is considered for evaluating and verifying the reinforcement proposal presented herein. It is worth noting that, during this stage, the different lining sections (along the tunnel alignment) are mainly subjected to combination of bending moments and axial compressive forces. The latter are transferred through the longitudinal joints between the segments of a ring. These load transfer areas are crucial to the whole lining system and oftentimes govern the

| ID     | Ecm (MPa) | fcm (MPa) | fck (MPa) | fctm (MPa) | fctk (MPa) |
|--------|-----------|-----------|-----------|------------|------------|
| C40/50 | 35,000    | 48        | 40        | 3.50       | 2.50       |
| C70/85 | 41,000    | 78        | 70        | 4.60       | 3.20       |

| ID          | Ecm (MPa) | fcm (MPa) | fck (MPa) | fctm (MPa) | fctk (MPa) | fR1k (MPa) | fR3k (MPa) | fR1m (MPa) | fR3m (MPa) |
|-------------|-----------|-----------|-----------|------------|------------|------------|------------|------------|------------|
| HPFRC70-8C  | 41,000    | 78        | 70        | 4.60       | 3.20       | 8.00       | 8.00       | 10.6       | 10.6       |
segment design since they have to resist high normal compressive forces acting on a limited contact area, generally smaller than the lining thickness; consequently, local tensile splitting stresses are also present. Hence, two major failure modes can be identified, tensile splitting failure and concrete crushing.

For the optimization process, the *Wehrhahnlinie* metro tunnel in Düsseldorf (Germany) is adopted as a reference.\(^{21,22}\) It is characterized by an internal diameter of 8300 mm and a lining thickness of 450 mm. Each ring is 1500 mm wide and composed of 7 regular segments plus 1 key segment. The lining geometry and reinforcement configuration initially adopted by the designers is used as reference (Figure 2). Furthermore, concrete class C40/50 (Table 1) and steel type B500A are considered (in accordance with the design specifications of the *Wehrhahnlinie* metro tunnel), whose mechanical properties are reported in Section 2.

The reference tunnel segment, reinforced by rebar only (traditional RC solution), is depicted in Figure 2. The reinforcement consists of 11 Ø 10 + 4 Ø 14 curved bars placed along the extrados and of 8 Ø 10 + 1 Ø 12 + 4 Ø 14 located along the intrados of the segment. Moreover, 12 Ø 12 closed stirrups are placed along the longitudinal joints to resist the local tensile splitting stresses.

The optimized hybrid solution combines higher strength concrete for the segment’s body (C70/85, Table 1) and HPFRC70-8C (Table 2) in the regions close to the longitudinal joints (Figure 3). This allows for a reduced lining thickness of 300 mm (33% reduction), without changing the internal diameter of the lining. The new lining thickness was determined by considering both, the required bearing capacity in the final state (Figure 4) as well as an adequate local behavior of the longitudinal joints. A local reinforcement solution was determined to provide a similar bearing capacity of the longitudinal joint with respect to the reference solution based on a combination of HPFRC and rebar. The regions of the segment where HPFRC is used are highlighted in red in Figure 3. Additionally, a local welded splitting reinforcement ladder composed of 15 Ø 10 + 15 Ø 10 + 12 Ø 8 rebar (B500A) was adopted (Figure 3), which has been found to provide an improved concrete confinement.\(^{23}\) The remaining volume of the segment features C70/85 concrete without fiber reinforcement. Moreover, 15 curved bars with a diameter of 14 mm (15 Ø 14) were placed along both the extrados and the intrados of the segment as bending reinforcement (Figure 3).

**FIGURE 2** Traditional RC reference solution: segment geometry and reinforcement (dimensions in mm)

**NUMERICAL VALIDATION: LOCAL BEHAVIOR OF LONGITUDINAL JOINTS**

The local behavior of longitudinal joints predominantly depends on the compressive stresses acting in the
direction of the axial ring force. They are transferred over a reduced contact surface and spread into the segment to achieve a uniform utilization of the cross-section, which generally leads to local transverse tensile and multi-axial compressive stress states in the area of load introduction. Hence, the portion of the segment where these stresses develop is a typical region of discontinuity (D-region). In order to properly describe the behavior of a longitudinal joint, especially in the post-cracking phase (when the post-cracking residual strength of HPFRC can be exploited), it is fundamental to validate the non-linear numerical and concrete crack models adopted. To this aim, the small-scale experiments reported in Smarslik and Mark are analyzed numerically and the results - experimental and theoretical - are compared to evaluate the model’s reliability.

4.1 | Test set-up

Concrete prisms with a size of 500 × 250 × 500 mm were previously tested under a line load configuration and with the two contact load surface geometries presented in Figure 5. In both configurations the contact area (Figure 5a,b) is 125 mm wide, corresponding to 50% of the sample’s width (250 mm). It should be noted that in the layout depicted in Figure 5b, the contact area is split into two identical surfaces, each having a width of 62.5 mm. For both cases, centric and eccentric loads were applied and analyzed. The eccentricity was conventionally assumed as 40 mm. A HPFRC layer was arranged over a height of 105 mm under the applied load, while in the remaining part of the sample (395 mm) normal
strength concrete was used. These two different layers were cast with a fresh-to-fresh technique. Among the many tests reported in Smarslik and Mark,13 two specific samples were selected for model validation (designation: HC_c_a and HC_ec_a, where c identifies a centric load, ec the eccentricities depicted in Figure 5 and HC the high strength concrete).

4.2 | Material modeling

Based on the data provided in Smarslik and Mark,13 the following mechanical properties are considered:

- for normal strength concrete: mean cylindrical compressive strength, $f_{cm} = 41.7$ MPa, Young’s modulus, $E_{cm} = 32,100$ MPa, and tensile strength, $f_{ctm} = 2.5$ MPa;
- for HPFRC: $f_{cm} = 85$ MPa, $E_{cm} = 47,600$ MPa and $f_{ctm} = 4.6$ MPa, post-cracking resistance (according to EN 1465125) $f_{R1m} = f_{R3m} = 10.6$ MPa.

The numerical simulations are performed using DIANA 10.1,26 which allows for a detailed description of the concrete’s post-cracking behavior. A smeared crack model developed by Rots, the total strain rotating concrete crack model, was adopted.27 It accounts for orthotropic softening and is therefore well-suited to model multi-axial stress states. Concrete in tension is assumed to behave linearly up to the mean tensile strength. In the post-cracking stage, based on available nominal residual flexural strengths ($f_{Rim}$), the uniaxial HPFRC tensile constitutive law is obtained by applying the simplified approach suggested by Mudatu.28 This law consists of three subsequent linear post-cracking branches. For the experimentally determined flexural strengths of the HPFRC, the tri-linearity is characterized by the following inflection points: $\sigma_1 = 2.73$ MPa-$w_1 = 0.017$ mm, $\sigma_2 = 4.17$ MPa-$w_2 = 0.37$ mm, $\sigma_3 = 3.03$ MPa-$w_3 = 2.59$ mm (Figure 6a). In case of plain concrete (without fibers), the post-cracking tensile law proposed by Hordijk was used.29

Since a smeared crack approach is adopted, it is necessary to transform the stress-crack-width law ($\sigma$-$w$) into a stress–strain relationship ($\sigma$-$\varepsilon$). Doing so, the crack width ($w$) is smeared over the element in equivalent strain ($\varepsilon$) by assuming a certain crack bandwidth, which is automatically determined by DIANA 10.126 and is approximately equal to the average element size. The uniaxial compressive behavior of concrete is described by means of the model proposed by Thorenfeldt30 and compressive strength increase due to lateral confinement was considered by means of the model introduced by Selby and Vecchio.31 Hence, the combination of material models can capture all relevant effects occurring for concrete elements subjected to high localized compressive stresses (see References 23 and 32).

The steel of all B500A rebar is defined as an elastic–plastic material with a bi-linear strain hardening up to the ultimate strength (Figure 6b) and an Young’s modulus ($E_s$) of 200,000 MPa. The von Mises yielding criterion is applied and the following mean values of the mechanical properties are adopted: $f_{sym} = 550$ MPa, $f_{sum} = 630$ MPa at a conventional ultimate strain of 2.5%.

4.3 | Numerical model

Two Finite Element models were adopted (Figures 7 and 8):

- a two-dimensional model based on eight-node quadrilateral iso-parametric plane elements having average dimensions of about 25 mm, that was found to capture very well the stress distribution in D-regions.33 A total of 300 elements are used for discretization (Figure 7) and two regions with different material properties are defined in order to reproduce the HPFRC layer in the area of load application (highlighted in Figure 7). The small amount of rebar in the D-region are modeled as embedded truss elements (Figure 7).
- a three-dimensional model in order to further verify the information obtained from the initial two-dimensional model with the aim to better capture phenomena related to the possible three-dimensional lateral confinement of concrete under compression in the region close to the applied load. The model consists of

![Figure 5](image-url)  
**FIGURE 5** Concrete specimens tested under line load with two different joint geometries: (a) HC_c_a and (b) HC_ec_a13 (dimensions in mm)
7500 twenty-node iso-parametric solid elements, as shown in Figure 8. The same average element dimensions (about 25 mm) were adopted in order to make the 2D and 3D models better comparable.

The numerical analyses were carried out under load control. Loads were applied (in both numerical models) as a uniform pressure acting on the loading surface. In case of central loading, the pressure is acting over the whole contact area in the center of the sample while, under eccentric conditions, the uniform pressure acts on a smaller area with an eccentricity of 40 mm (Figure 7b).

### 4.4 Numerical results

Results obtained from the numerical analyses are reported in Figure 9 in terms of total load over vertical displacement. Figure 9a shows the experimental and numerical results of the centrally loaded samples while Figure 9b exhibits the comparison of eccentrically loaded specimens. A good agreement between numerical and experimental results can be observed in terms of stiffness and bearing capacity. In both cases the experimental results provide the highest bearing capacity, followed by the 2D (−3%, −7%) and the 3D models (−10%, −11%). It should be noted that the initial lower stiffness of the experimental curve obtained from specimen HC_c_a was due to irregularities of the concrete surface (which was not perfectly smooth) and to the deformations of the 3 mm hardwood interlayer.

In summary, the numerical models as well as the material assumptions (Section 4.2) and their modeling (Section 4.3) are able to reproduce the behavior of samples tested in Smarslik and Mark. Hence, they are representative of the local behavior expected at the longitudinal joints of the tunnel segments in the final state.
5 | NUMERICAL STUDY: TUNNEL SEGMENT DURING FINAL STATE

5.1 | Test set-up

In order to reproduce the final state conditions of tunnel segments, two typologies of experimental tests are generally possible: testing of a whole lining ring or of a single segment. Blom\textsuperscript{34} carried out tests on full rings to verify analytical and numerical models for predicting ring ovalization and the development of internal forces. Hemmy\textsuperscript{35} on the other hand, performed tests on single full-scale segments to evaluate their ultimate bearing capacity under final loading conditions. While full ring tests adequately capture the kinematics and loading conditions of real linings, they require an extensive and complicated test set-up. Single segment tests tend to over-simplify kinematics and loading conditions. Hemmy\textsuperscript{35} reproduced the ground pressure by only two concentrated vertical loads instead of more realistic
distributed radial loads; furthermore, the boundary conditions at the longitudinal joint were simplified as a hinge.

Although the authors believe that, if the main aim is to determine ultimate bearing capacities in the final state, testing a single tunnel segment can be sufficient, existing testing procedures have to be extended and refined to eliminate the aforementioned shortcomings. The two major challenges are the application of realistic radial loads (with high magnitude) and the reproduction of the boundary conditions at the longitudinal joint. Such a new testing procedure was developed by the authors and is currently being verified. It provides the basis for the subsequent numerical analyses.

Hence, the results reported hereafter will be used, on one hand, to validate the efficiency of the proposed, optimized, hybrid lining segment design and, on the other hand, serve as a preliminary investigation of parameters and reactions required for the practical execution of the experiments. The loads are generated by vertically \( F_v \) and horizontally \( F_h \) aligned pressure jacks, which transform into four (evenly spaced) distributed radial loads \( F_R \) and a reactive contact pressure at the longitudinal joints \( F_L \). To realize multiple, realistic failure mechanisms of the segment, the two pressure jacks \( F_v \) and \( F_h \) are actively controlled. A draft is presented in Figure 10.

**Figure 12** Front view of the three-dimensional model used for simulating the tunnel segment with applied radial loads, boundary conditions and the lateral pressure applied at the longitudinal joints (dimensions in mm)

**Figure 13** Conventional geometric configuration of the longitudinal joint under three loading scenarios: centric (a), outward (b) and inward (c) eccentric uniform pressure applied on the contact surface

**Figure 14** Optimized geometric configuration of the longitudinal joint as proposed in Smarslik and Mark\textsuperscript{13} adopted for the hybrid segment with evidenced the three loading scenarios: centric (a), inward (b) and outward (c) eccentric uniform pressure applied on the double contact surfaces
5.2 | Material modeling

The numerical analyses are carried out by referring to mean values of mechanical material properties (Table 1 and Table 2). The constitutive models described in Section 4.2 are used for simulating the embedded rebar adopted for the model and the concrete behavior in tension and in compression, since their effectiveness was already validated in Section 4.

5.3 | Numerical model

A three-dimensional model discretized by twenty-node iso-parametric solid elements is used for simulating the tunnel segment behavior in the final state (Figure 11). The average dimension of solid elements is around 40 mm. For computational efficiency, only one quarter of the segment was simulated by exploiting the double symmetry in terms of applied loads and boundary conditions (Figure 11). According to the testing device previously described, four radial loads are applied to the segment, as shown in Figure 12, which also depicts the boundary and symmetry conditions. It is worth noting that a uniform pressure is applied perpendicular to the longitudinal joint (Figure 12) to ensure global vertical equilibrium in reaction to the applied radial loads. Consequently, the radial loads and the pressure acting on the joint are increased proportionally during the numerical simulations.

Two tunnel segment solutions are investigated: the traditional RC reference having a thickness of 450 mm (Figure 2) and the hybrid solution characterized by a reduced thickness (300 mm) in combination with the use of HPFRC layers in the longitudinal joint regions (Figure 3). For the reference segment, a conventional geometric joint configuration with one contact area and a gasket at the extrados is analyzed in order to reproduce the Wehrhahnlinie longitudinal joint configuration (Figure 13). For the hybrid solution, two different geometric configurations are adopted: the conventional one (Figure 13) and a new geometry with a central gasket and two separated contact areas (Figure 14). For each configuration, three different loading scenarios are considered. Figure 13a depicts the conventional geometric joint configuration adopted for the tunnel lining segments investigated herein. It features a central contact area with a width (a) of 230 mm, corresponding to 51% of the lining thickness (t). In the hybrid solution (t = 300 mm), the contact area width decreases proportionally in order to remain about 51% (155 mm) of the total lining thickness (Figure 13a). In case of centric loading, the whole joint width is subjected to a uniform pressure (Figure 13a). Two eccentric load cases with an outward eccentricity (Figure 13b) and an inward eccentricity (Figure 13c) are considered. The eccentricity is equal to 0.28\(t = 64.4\) mm\(^{19,36}\) and it is conservatively the same for both segments, leading to 64.4/450 = 0.14\(t\) (<1/6\(t\), for the reference specimen) and 64.4/300 = 0.21\(t\) (>1/6\(t\), for the hybrid segment), which means the formation of a lateral edge tensile force for the reduced thickness configuration.\(^{19}\)

Figure 14a presents a new, optimized longitudinal joint configuration, as proposed in Smarslik and Mark.\(^{13}\) In this

![Figure 15](image1.png)  
**Figure 15** Numerical results in terms of total load applied to the segment longitudinal joints of the traditional RC reference solution (t = 450 mm) under centric and eccentric loading scenarios

![Figure 16](image2.png)  
**Figure 16** Numerical results in terms of total load applied to the segment longitudinal joints in case of centric loading. Comparison between the traditional RC reference solution (t = 450 mm) and the two hybrid solutions.
case, the gasket groove is moved to the center of the segment for better protection against spalling and cracking, which leads to two contact areas next to the groove (splitted joint configuration). Since only the hybrid segment \((t = 300 \text{ mm})\) is analyzed for this solution, each of the contact surfaces has a width of \(155/2 = 77.5 \text{ mm}\), which equals the total contact width of the conventional joint configuration for the hybrid solution. Furthermore, the same three loading scenarios (centric, inward and outward eccentricity of 64.4 mm) are analyzed to ensure comparability of the results. While the pressure is distributed evenly to both contact strips under centric loading, it is unevenly distributed under eccentric conditions (93%–7%).

5.4 | Numerical results

The two tunnel segment solutions, the different joint configurations and loading scenarios occurring at the longitudinal joints (presented in Section 5.3) are considered within a parametric study. For each numerical analysis, a progressive increment of the loads up to failure was applied in order to determine the crack development as well as the post-cracking stiffness and their effects on the bearing capacity, which is the primary output parameter focused herein. Figure 15 shows the numerically obtained maximum loads of the traditional RC reference tunnel segment by considering the three different loading scenarios described above. For the centric loading condition (Figure 13a), corresponding to an ideal contact along the surface of the longitudinal joint, a maximum load of 18.1 MN is reached. Failure of the specimen is induced by local concrete crushing due to excessive compressive stresses in the region close to the longitudinal joint. Although the bearing capacity of the specimens with eccentric load decreases to almost half in comparison to the centric case, higher compressive stresses are reached for both the inward (+23%) and outward (+12%) eccentricity.

Figure 16 presents a comparison between the two tunnel segment solutions (traditional and hybrid) for the conventional and optimized joint geometries under centric loading conditions. For the traditional RC reference

![Figure 15](image15.png)

**Figure 15** Numerical results: minimum principal stresses (a) hybrid solution with traditional joint configuration and (b) hybrid solution with splitted joint configuration
solution this corresponds to the scenario reported in Figure 13a while two joint configurations are considered for the hybrid solution, corresponding to Figures 13a and 14a. The results reported in Figure 16 clearly evidence that the bearing capacity of the hybrid solution (with a segment’s thickness reduced by 33%) is similar to the one of the traditional design. Loads decrease only minimally for the hybrid segment with a conventional joint configuration (−18%) and even increase for the splitted joint configuration (+9%). Consequently, the optimized hybrid segment solution efficiently utilizes the HPFRC layers close to the longitudinal joints, especially when adopting the double contact surfaces configuration, to increase the ultimate bearing capacities. In addition, it should be noted that in case of hybrid segment, having a splitted joint configuration instead of the traditional one, the failure mechanism changes from splitting to crushing, as proven by the contact pressure level at the longitudinal joint (Figure 17). In fact, when considering a “traditional” joint configuration (Figure 17a), at maximum...
load the contact pressure is equal to 77.7 MPa (about \( f_{cm} \)), while for the “splitted” one it is around 102.9 MPa (Figure 17b). The latter value is about 30% higher than \( f_{cm} \), as a result of the confinement induced by transverse compressive stresses; the increment of strength is in good accordance with Kupfer et al.\(^3\) for a biaxial stress condition. Hence, for the hybrid segment with the optimized joint geometry, the highest possible contact pressure is achieved, leading to a crushing failure. In order to better study the local phenomena occurring along the longitudinal joint, Figure 18 reports the crack pattern exhibited by the two hybrid segments with different joint configurations at maximum load. In Figure 18a it can be clearly pointed out a crack along the segment, highlighting a typical splitting collapse mechanism, since a traditional longitudinal joint configuration is used. On the contrary, in case of the hybrid solution with splitted joint configuration, splitting tensile stresses are well controlled up to crushing (Figure 18b).

The enhanced structural performance of the hybrid segment can be also observed for eccentric loads. Figure 19 compare the ultimate loads for the traditional RC reference segment with a thickness of 450 mm and the conventional joint geometry to those of the hybrid segment with a thickness of 300 mm and the splitted joint configuration (two contact areas), since it is the most promising joint configuration as proven in Figure 16. In all cases, the hybrid segment provides a better bearing capacity: +9% for centric loading, +16% for an inward, and +22% for an outward eccentricity. Furthermore, by investigating the failure mechanisms at the maximum load, it can be concluded that the addition of local HPFRC layers, together with an adequate geometric configuration of the contact surfaces, enables a transition of failure mechanisms from tensile splitting to compressive concrete crushing. In other words, the combination of local HPFRC layer, rebar and an enhanced longitudinal joint configuration provide a noticeable bearing capacity and resistance against tensile splitting stresses.

6 CONCLUDING REMARKS

In the present paper, the structural feasibility of a new hybrid solution for precast tunnel segments is evaluated for a typical metro tunnel lining (internal diameter of 8300 mm) by means of a parametric numerical study aiming at simulating the behavior of the lining in the final (service) state. Three different design solutions of precast tunnel segments were considered: (1) a traditional RC reference segment with a thickness of 450 mm and conventional geometric layout of the longitudinal joint, (2) a hybrid segment with higher strength concrete in combination with a HPFRC layer at the longitudinal joint and a reduced HPFRC layer at the longitudinal joint and a reduced thickness of 300 mm, and (3) the same hybrid segment with an improved joint geometry. The numerical simulations of the final state are based on the boundary conditions and applied loads assumed for the developed testing device.

Based on the numerical results obtained, the following conclusions can be drawn:

- the hybrid solution featuring a combination of high strength reinforced concrete for the segment’s body and additional HPFRC layers at the longitudinal joints of the tunnel segment proves to be particularly effective, especially when the geometric configuration of the joint is modified by moving the gasket to the center of the segment which entails two contact surfaces with the gasket groove in the middle;
- the hybrid tunnel segment solution enables a reduction of the lining thickness of about 33% (300 mm instead of 450 mm) while maintaining the initial bearing capacity of the traditional RC reference solution;
- the improved structural performance of the hybrid solution proposed also holds for unfavorable loading conditions occurring in the longitudinal joints, such as outward and inward eccentricities;
- the combination of local HPFRC layer, rebar and an enhanced longitudinal joint configuration provide a noticeable bearing capacity and resistance increase against tensile splitting stresses (in fact, instead of a tensile splitting failure, a compressive crushing failure was observed);
- the combination of high-performance materials and geometric modifications presented herein lead to significant volume reductions of precast tunnel segments keeping the original structural performance;
- the hybrid design offers new perspectives in terms of reduced volume of disposal materials and boring machine size leading to a probable reduction of CO\(_2\). These aspects are expected to further improve tunneling projects’ economic and ecologic feasibility.

NOMENCLATURE

\begin{tabular}{ll}

\( E_{cm} \) & modulus of elasticity of concrete \\
\( E_s \) & modulus of elasticity of steel \\
\( f_{ck} \) & characteristic compressive cylinder strength of concrete at 28 days \\
\( f_{cm} \) & mean value of concrete cylinder compressive strength at 28 days \\
\( f_{ctk} \) & characteristic axial tensile strength of concrete \\
\( f_{ctm} \) & mean value of axial tensile strength of concrete \\
\( f_{R1k} \) & characteristic residual flexural tensile strength evaluate for CMOD of 0.5 mm \\
\end{tabular}
DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Trabucchi I, Smarslik M, Tiberti G, Petraroia DN, Plizzari GA, Mark P. A hybrid solution proposal for precast tunnel segments. Structural Concrete. 2021;22:1534–1548. https://doi.org/10.1002/suco.202000629