Analysis and design of an innovative solution for tunnels using elastic-plastic stress fields

STEFANO CAMPANA AND AURELIO MUTTONI

Institute of Civil Engineering (IIC), Structural Concrete Laboratory (IBETON)
Ecole Polytechnique Fédérale de Lausanne (EPFL), 1015 Lausanne, Switzerland
stefano.campana@epfl.ch

Abstract

For the conception of cut-and-cover tunnel, two solutions are usually considered to define the cross-section : an arch/vault or a frame. The vault enables an optimal static behavior in case of a large soil cover and symmetric loads. However, this solution faces some constructive issues. The construction process of a frame is simpler and more cost efficient, but its static behavior turns out to be less suitable for large soil covers. A research performed at EPFL allowed defining an innovative solution for the transverse section. This solution is a mix of a frame and a vault. It combines the static and constructive advantages of both solutions. This shape was chosen for several projects that are currently under way in Switzerland. The performance of this transverse section depends on the strength and ductility of its nodes. This paper presents an overview of the first results following both theoretical and experimental investigations that are currently under way about the behavior of nodes subjected to various load configurations. The theoretical part is used for the conceptual design and the optimization of bars details aiming at satisfying both ductility and strength requirements. The specimens were modeled and analyzed with the elastic-plastic stress fields method. This method enables to predict the failure modes and strengths of the specimens. The experimental part consists of a series of tests on four full scale specimens. These tests pointed out that the loading type and the bar disposition significantly influence the nodes areas.

1. Introduction

Cut-and-cover tunnels are structural types used for tunnels with relatively shallow earth cover and to improve the environmental impact of roads and railway lines (noise reduction, better integration in the landscape, continuity of the ground surface). Figures 1a, 1b and 1c show schematically the construction sequence for a cut-and-cover tunnel. After the excavation, the structure is built in the open and subsequently covered by earth. This construction method allows reducing the technical difficulties and higher costs related to conventional tunnel construction. In the current practice, two cross sections are typically used : as a vault (figure 1d) or as a frame (figure 1e). Neither solution is fully optimal. While the vault offers a good behavior if the cover is symmetrical, it is less appropriate for unsymmetrical configurations. Its shape leads to outwards thrust forces that can lead to fragile failure modes. Its construction requires curved formwork and is therefore complicated. The frame allows for simple formwork, but its static behavior is often less efficient. A research at EPFL has led to an innovative solution halfway between the two classical solutions (figure 1f). This solution, with its polygonal shape, benefits from the static performance of the vault while using simpler formwork. In the case of the cut-and-cover tunnel investigated in figure 2, the behavior differs strongly if the structure is subjected to a symmetrical (figure 2a) or unsymmetrical loading (figure 2b). The figure shows both the thrust line and the deflected shape of the structure. In particular, the thrust line shows that some corners tend to close, if the thrust line passes on the inside of the corner while others tend to open, if the thrust line passes on the outside of the corner.

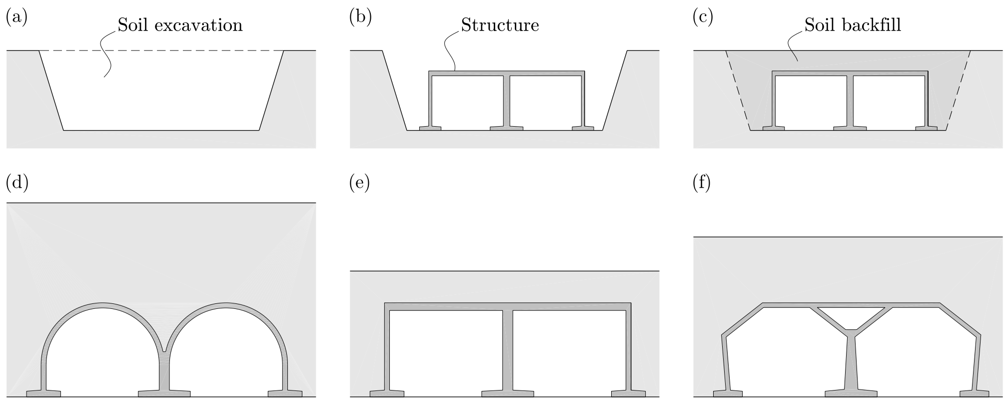

Figure 1: (a)-(c) Construction sequence for cut-and-cover tunnel – Typically used cross section : (d) vault, for large earth cover (e) frame, for small earth cover (f) innovative polygonal shape

The corresponding failure mechanisms for symmetrical and unsymmetrical loading are shown in figures 2c and 2d. The nodes and regions close to them are governing as deformations concentrate in these places. In the following, some aspects relative to design of the critical nodal regions, notably their strength and ductility, are investigated both experimentally by testing of specimens and numerically by a simulation based on the elastic-plastic stress fields (EPSF).

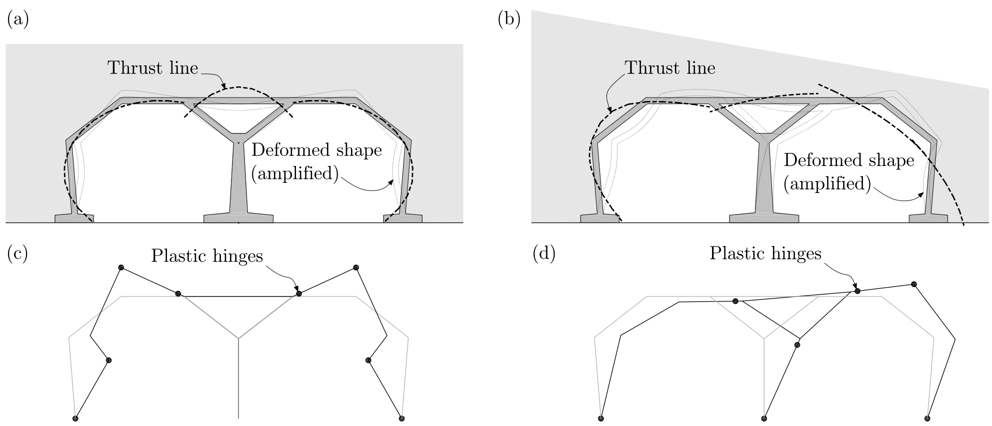

Figure 2: Behavior of cut-and-cover tunnel : (a) symmetrical loading (b) unsymmetrical loading – Failure mechanisms in case of : (c) symmetrical loading (d) unsymmetrical loading

2. Structural behavior and soil-structure interaction

Research projects focusing on the soil-structure interaction [1, 5] have demonstrated the importance of the ductility of the structure on the dimensioning of cut-and-cover tunnels. It was shown that the actions of the soil on the structure decrease if the deformations of the structure increase. With increasing deformation, the soil gradually goes from an elastic to a plastic regime, with failure mechanisms in the soil and the building-up of thrust arches in the ground, which reduce the action of the soil on the structure. Two main parameters influence a structure's deformation capacity : its stiffness (elastic regime) and its ductility (plastic regime). As shown in figure 3, the deformation corresponding to the equilibrium point between the soil and the structure differs depending on the structure's behavior. Thus, structure A, which is stiffer in its cracked configuration, is subjected to a larger loads from the soil than structure B, which is more flexible. Figure 3b show that the equilibrium solution can only be reached if the structure does not fail at a lower deformation level. It is therefore necessary to avoid any premature failure, for instance fragile failure modes in shear or failure modes involving the spalling off of concrete in compression [5]. The importance of the structure's deformation capacity with respect to the action of the soil highlights the necessity of a specific study of the behavior of nodal regions, where deformations concentrate (figures 2c and 2d). This was done by a series of tests and by numerical simulations.

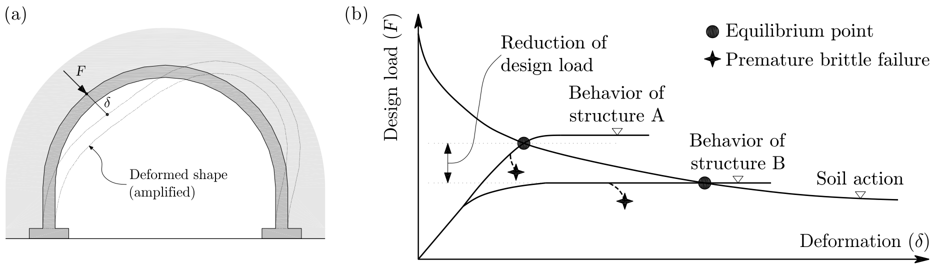

Figure 3: Determination of the design load as a function of the structure's behavior

3. Experimental program

A series of tests was performed on four full-scale specimens representing the corner of a cut-and-cover tunnel as a function of the type of loading applied and of the type of reinforcement detail (figure 4a) [4].

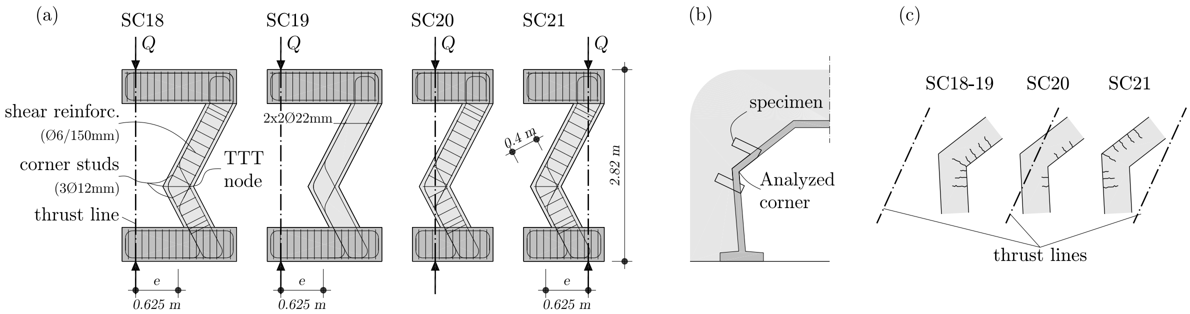

Figure 4: (a) geometry of specimens with reinforcements bars and load configuration (b) location of the specimens in the section of cut-and-cover-tunnel (c) location of the thrust lines

The width of all specimens is 300 mm. The controlling parameter of each test was the location of the thrust-line, materialized by the eccentricity e of the applied loading. The reinforcement and anchorage details were adapted to correspond to the acting internal forces. Figure 4b shows the location of the specimen in the section of the cut-and-cover tunnel. Figure 4c shows the location of the thrust line in the cut-and-cover tunnel corresponding to all specimens. Specimens SC18 and SC19 were subjected to an opening of the corner, while specimen SC20 had no eccentricity of the loading and specimen SC21 was subjected to a closing of the corner. All specimens had the same nominal flexural reinforcement ($\rho_{\text{nom}} = 0.77\%$, $f_y = 572$ MPa). The actual number of bars varied between 2x2Ø22 mm in normal areas to 2x6Ø22 mm in areas of bar lapses [4]. Specimens SC18, SC20 and SC21 had a very low transverse reinforcement ratio ($\rho_w = 0.063\%$, $f_{y,w} = 646$ MPa) complemented by three Ø12 mm two-headed studs in the corner ($f_{y,\text{studs}} = 538$ MPa). Specimen SC19 did not have any transverse reinforcement. It serves as a reference specimen as transverse reinforcement is typically not used in practice. The concrete compressive strenght on cylindres f_c varied from 32.5 MPa to 36.4 MPa. The rotations, displacements and surface deformations were measured during the tests to follow the global behavior of the specimen [4]. The deformations at the concrete surface were measured in the corner region at two load levels, using a demec mechanical strain gauge. The last demec measurements was taken close to the failure load (about 90%). Figure 5 and figures 6a to 6d illustrate the results of these tests.

	$Q_{R,\text{test}}$ [kN]	$Q_{R,\text{EPSF}}$ [kN]	$Q_{R,\text{test}}/Q_{R,\text{EPSF}}$** [-]
SC18	97	107*	0.91*
SC19	59	47	1.26
SC20	350	389	0.90
SC21	347	344	1.01

* With an adapted yield strength for studs [3]
** mean = 1.02 ; COV = 0.16

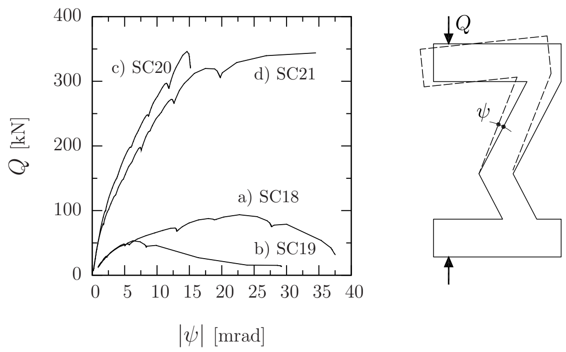

Figure 5: Results of tests and simulations – Curves load Q vs relative rotation of the corner $|\psi|$

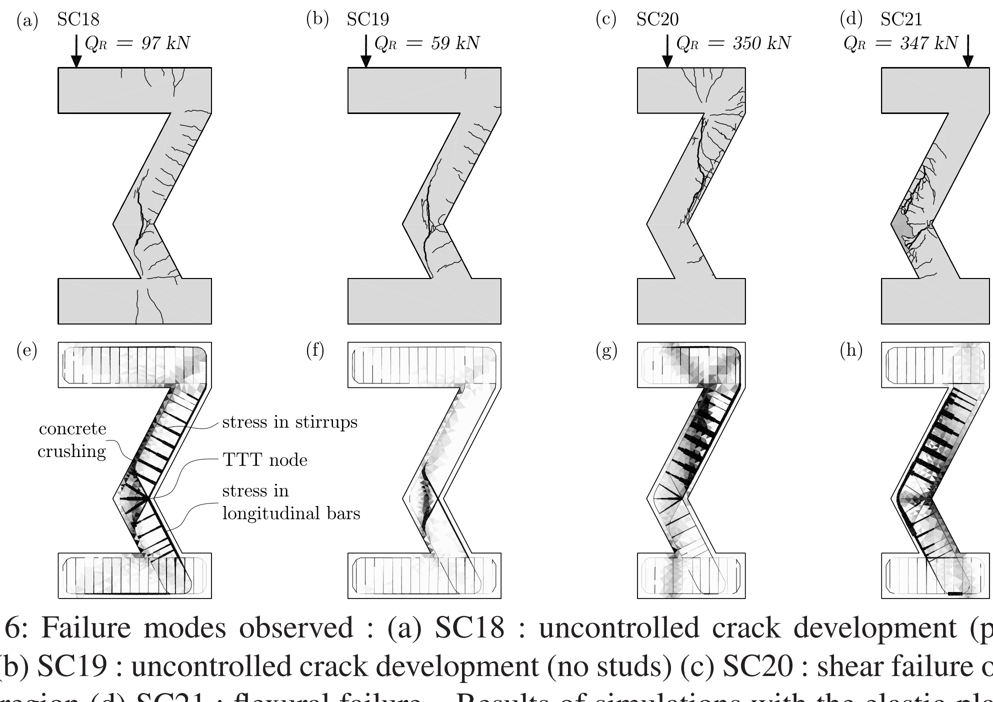

Figure 6: Failure modes observed : (a) SC18 : uncontrolled crack development (pull-out of studs) (b) SC19 : uncontrolled crack development (no studs) (c) SC20 : shear failure outside the corner region (d) SC21 : flexural failure – Results of simulations with the elastic-plastic stress fields method : (e) SC18 (f) SC19 (g) SC20 (h) SC21

– Specimen SC18 (large opening eccentricity) was subjected to an opening of its corner. The strength reached was very low, due in part to the large eccentricity of the loading that caused an important flexural effect. Also, the anchorage of the three two-headed studs in the corner was not sufficient to control the opening of the vertical critical crack in the corner region (figure 6a). The failure in the corner occured at a node subjected to tension in three directions (TTT-node, figure 4a). This type of node is known to be problematic and should be avoided in practice. Indeed, the studs were pulled out of the concrete. The failure mode shown in figure 5(curve a) was rather ductile, however, as the studs slipped and did not fracture.

- Specimen SC19 (large opening eccentricity) exhibited a failure mode similar to SC18, but with a reduced strength. Figure 5(curve b) shows that the failure mode was more fragile. In this case, the opening of the vertical critical crack in the corner region was absolutely not controlled in the absence of any transverse reinforcement (figure 6b).
- Specimen SC20 (without eccentricity) reached a higher load. The absence of eccentricity contributed significantly to this behavior. The specimen failed in a brittle manner in shear outside the corner region (figure 5(curve c) and figure 6c).
- Specimen SC21 (small closing eccentricity) was subjected to a closing of its corner. The load reached corresponds to the expected one for a closing corner, for which the behavior and adequate reinforcement detailing are better known. The specimen failed in bending with spalling of the cover concrete on the tension side (figure 5(curve d) and figure 6d).

4. Analysis by elastic-plastic stress fields

The elastic-plastic stress fields method (EPSF) is an application of the stress-fields theory [2]. It allows a refined study of the behavior of reinforced concrete elements and is based on the lower bound theorem of the theory of plasticity. It allows determining a compatible stress field in static equilibrium with the applied loads and respecting the plasticity conditions of the materials. When increasing the load, this method allows to identify failure mechanisms and thus to approximate the exact solution. The main hypotheses of this method are :

- The tensile strength of concrete is neglected. The compressive strength of concrete is modeled following an elastic-plastic relationship. The concrete's plastic strenght in compression depends on its uniaxial compressive strength f_c and on its transverse strain state. This is because a transverse strain decreases the concrete compressive strength [6].
- The behavior of steel in tension and in compression is modeled by an elastic-plastic relationship. The plastic strength of the steel is equal to its yield stress f_y. Perfect bond is assumed for reinforcing elements.
- The direction of the principal stresses is considered parallel to that of the strains.

5. Comparison of experimental tests results with EPSF method

Table in figure 5 and figures 6e to 6h show the results obtained with the EPSF method [2], both regarding the maximum load and the failure mode.

- The strength calculated for specimen SC18 is significantly larger that the actual strength. This is because the EPSF calculation considers a perfect anchorage of the reinforcing bars. This is why the pull-out failure mode was not identified. This mode of failure can however be reproduced a posteriori by following the proposal by Fernández Ruiz, Muttoni and Kunz [3], which considers an adapted yield strength for the corner studs that takes into account their geometry and the location of the critical crack respective to the anchor heads.
- The strength calculated for specimen SC19 was, on the contrary, very conservative. This is because the failure mode that occurred was mainly controlled by the tensile strength of the concrete, which is neglected by the EPSF method. The failure mode was correctly identified, however (figures 6b and 6f).
- The strength and the failure mode were correctly predicted for specimens SC20 and SC21.

6. Study of the overall behavior

As shown in figure 3, the study of the overall behavior of the structure is of paramount importance, as it determines the action of the soil on the structure. One of the key advantages of the EPSF method is that it allows studying in the same manner the overall behavior of the structure and that of a particular detail. As shown in figure 7, the entirety of the structure can be modeled to identify its weak points, where the first failures occur, and the corresponding failure mechanisms. In order to obtain a better performance of the overall structure, these critical zones can be analyzed to improve their performance with respect to strength and deformation capacity.

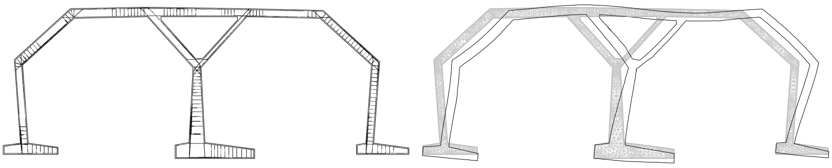

Figure 7: Study of the overall behavior of an actual cut-and-cover tunnel with the EPSF method

7. Conclusions and future developments

The innovative polygonal shape proposed for cut-and-cover tunnel (figure 1f) allows combining the advantages of the classical vault and frame shapes. The internal forces in a cut-and-cover tunnel directly depend on the structure's deformation capacity, which, in turn, depends on the deformation capacity of its nodal regions, where deformations concentrate. The experimental investigation has shown that the deformation capacity of the nodes strongly depends on the constructive detailing and the applied loading. The behavior and the ultimate strength of opening corners (SC18 and SC19) are not satisfactory. For specimen SC18, the TTT-node has caused a premature failure. The reference specimen SC19 has demonstrated the necessity to control the opening of the vertical crack in the corner. If the failure mode is not controlled by concrete in tension (which should be avoided anyway) and if problematic TTT-nodes are avoided, the EPSF method is promising to predict the performance of constructive details in the nodal regions, with a correct identification of the failure modes and of the failure strength. The following of this research will focus on the conception of details that offer a more ductile behavior and allow larger deformations of the structure in order to decrease the applied loading for opening corners.

References

[1] AFTES, Stabilité des tunnels par la méthode convergence-confinement, *Tunnels et ouvrages souterrains*, Vol. 32, pp. 70-81, France, 1979.

[2] Fernández Ruiz M., Muttoni A., On Development of Suitable Stress Fields for Structural Concrete, *ACI Structural Journal*, Vol. 104, nb 4, pp. 495-502, Farmington Hills, USA, 2007.

[3] Fernández Ruiz M., Muttoni A., Kunz J., Strengthening of flat slabs against punching shear using post-installed shear reinforcement, *ACI Structural Journal*, accepted for publication.

[4] Campana S., Essais sur spécimens d'un angle d'une tranchée couverte en béton armé à section transversale polygonale, EPFL, IBETON, 62 pp., Lausanne, Switzerland, April, 2010.

[5] Plumey S., Interaction sol-structure dans le domaine des tranchées couvertes, *EPFL Thesis*, nb 3714, 299 pp., Lausanne, Switzerland, January, 2007.

[6] Vecchio F. J., Collins M. P., The modified compression-field theory for reinforced concrete elements subjected to shear, *ACI Structural Journal*, vol. 83, pp. 219-231, Farmington Hills, USA, March - April, 1986.