Within the first portion of this thesis, selected aspects of tunnel lining design are introduced and compared. Traditional tunnel lining design relies on comparatively simple structural models to attain design structural forces, and on simplified load spreading assumption to address the effects of local loadings, such as those resulting from jack thrust forces. These methods, although efficient and effective at providing first-order estimations of the expected forces in tunnel linings, cannot accurately depict the complex interactions that develop as a result of concrete cracking and stress redistributions within a segment during loading. The literature provides a number of differing structural models that may be used for tunnel design, as well as a number of divergent loading assumptions which, when applied to the same engineering problem, can result in a range of design stresses and stress resultants. Upon comparison of the predictions of these models it becomes apparent that, in order to better evaluate the loadings to which tunnel linings are subjected, more detailed structural models must be used and better methods must be incorporated into the design process in order to accurately account for the amount of loadings to which linings are actually subjected.

In addition to the discussion of loading assumptions and structural models, some practical methods provided in design guidelines with which to account for the influence of steel fibers as part of the reinforcement scheme are discussed. As the post-failure tensile strengths of the types of steel fiber reinforced concrete (SFRC) typically used in practice are most often less than their pre-failure strengths, SFRC, as accounted for in the design standards, cannot be used as a viable post-cracking reinforcement during design for all structures. Tunnel linings, however, are ideal candidates for SFRC reinforcement, as they form a statically indeterminate structure and can therefore allow for a stress distribution upon cracking. Steel fibers can also be used as a crack-width control measure, and therefore to insure that serviceability limits are upheld. Within a later portion of this thesis it is shown that pure SFRC tunnel lining structures have a significant amount of post-fracture structural strength, however, the inability to account for this properly within the design codes is a result of the most often purely linear elastic calculations called for in engineering standards. In order to properly account for the effect of SFRC within a structure, the non-linear redistribution of stresses within a structure that occurs after concrete fracture must be accounted for. To do so, and to incorporate the
effects and interactions between steel fiber and traditional reinforcement, non-linear models must be used.

In order to address existing issues with the modeling of SFRC and hybrid reinforcement schemes consisting of SFRC augmented with standard reinforced concrete (RC), a novel Finite Element (FE) modeling concept is introduced. Within this modeling concept, the fracture and post-fracture behavior of plain concrete (PC), SFRC, and hybrid SFRC and reinforced concrete (RC) structures can be explicitly modeled. The compressive behavior of the concrete within the FE mesh is modeled using standard linear elastic triangular or tetrahedral finite elements, i.e. “bulk” elements. The fracture behavior of the concrete is modeled by incorporating non-zero-thickness interface-solid elements (ISEs) between each standard linear element. The material behavior of the ISEs can be modified to account for PC fracture or SFRC fracture. If SFRC fracture is modeled, a multi-scale traction-separation law as introduced by Zhan (2016) that is able to account for the variance in fiber type and geometry is used as a basis for the post-failure response of the ISEs. Discrete reinforcement is incorporated within the modeling framework as 1D beam or truss elements that are tied to the “bulk” by means of a novel frictional-contact based tying scheme.

The frictional-contact based tying scheme creates a displacement constraint between an arbitrary “control point” on the truss or beam and its projection on the “bulk” mesh. The displacement is perfectly constrained in the directions perpendicular to the truss, however the “slip” behavior of the truss, i.e. the displacement between the control point on the truss and its projection point along the axis of the truss, is assumed to follow the interface stress-slip law for reinforcement bars as provided by the International Federation for Structural Concrete (2013). This modeling scheme provides a technique with which arbitrary reinforcement layouts can accounted for even in, or especially in, cases in which the meshes of the 1D bar and the bulk meshes are incompatible. Using this method, no extra degrees of freedom are created through the addition of the reinforcement except for those of the 1D elements. The proposed method is compatible with the proposed interface-based modeling scheme, but can also be used with non-interface enhanced meshes. As the discrete reinforcement is only tied to the bulk elements within a mesh, the modeling method is able to simulate crack propagation “around” the rebar, even in 2D. Various experimental as well as numerical tests are provided to verify and validate the proposed numerical technique in 2D as well as 3D.

In the final section of this thesis, the proposed modeling technique is used to evaluate the structural response of PC, SFRC, and hybrid SFRC-RC segmental lining systems. As per the design standards, the loading response of individual segments as well as of the entire lining ring is investigated. In order to investigate the structural response of the entire lining system, a modeling methodology is introduced in which the deformations measured along the boundaries of a lining ring within a full-scale process-oriented 3D tunnel simulation are applied as boundary conditions to a simplified model of only a tunnel lining ring. In doing so, the model of the tunnel lining ring is very finely meshed using the SFRC and RC modeling methodology discussed above. Additionally, joint segmentation is explicitly accounted for by using ISE’s with zero tensile strength as contact surfaces between consecutive segments. It is shown that the structural forces obtained using this modeling methodology are within the acceptable ranges that 3D numerical and beam-spring models...
produce. Using this modeling methodology, the response of different lining designs to different loadings is investigated. Specifically, three cases are investigated: the normal loadings, bending-dominant loadings in which the moment in the lining ring is increased, and normal force dominant loadings in which the normal force and moment are both increased. In general, no structural failure of the lining system is observed and, with regard to crack widths, full SFRC linings perform better than all other designs.

Analysis of the normal tunnel loadings shows that even plain concrete tunnel linings do not experience significant cracking upon loading. This indicates that tunnel lining segments are much more robust against standard tunnel loadings than often assumed. The bending dominant load case, however, indicates that, especially at areas of high bending, i.e. the tunnel crown, bending reinforcement is required, as bending may lead to cracking at the tunnel crown. Various segment designs are investigated and it is shown that intelligent placement of SFRC along the inner surface results in a segment that behaves better with respect to crack formation than a traditionally reinforced segment and almost as well as a full SFRC segment. Similar results can be observed in the normal force dominated load case. In this load case, however, the main failure mechanism transitions from a bending-type failure to a “chipping”-type failure, as chipping of the longitudinal joint is often observed. Here again, it is shown that SFRC, rather than RC, most efficiently prevents crack development. In addition, hybrid SFRC-RC designs are investigated in which it is shown that with the correct placement of SFRC at sensitive areas, the post-cracking response of a full SFRC lining can be effectively replicated. Additionally, it is observed that high-strength medium length steel fibers provide better reinforcement than significantly longer normal-strength fibers.

In order to address local loadings due to the application of the jack pressure at the face of the segment, individual segment tests are performed. In a first series of tests, hybrid PC-SFRC segments as well as RC segments are investigated with respect to the splitting cracks that develop within the segments upon jack pressure loading. Again it is shown that pure SFRC samples are able to limit cracking response the most effectively. In this case, none of the hybrid variations with “intelligently” placed SFRC areas are able to reproduce the full SFRC segment response. Additionally, it is shown that SFRC more effectively limits crack formation than even RC. A further case often discussed in design, lack of segment bedding, is also investigated. In this case it is assumed that the segment is loaded by both jacks, however the segment is only supported by one jack due to improper installation of segments within the lining ring. Hybrid SFRC-PC segments are investigated and again it is shown that the complete SFRC segment performs best. In this case however, it is shown that the addition of an SFRC “band” along the font face of a segment can significantly increase the load bearing capacity of the poorly bedded segment, as well as decrease the areas of the segment in which cracks having super-critical crack widths develop.

With regard to the investigated loading scenarios, this thesis shows that, among all other segment types, full SFRC segments are more efficient than RC segments at resisting crack formation due to TBM induced loadings, and have no significant structural disadvantage when compared to traditional RC, at least in the investigated scenarios. Additionally, it has been shown that, with exact placement of SFRC within a tunnel segment, tunnel segments can be produced that resist crack-formation almost as efficiently as full SFRC segments, with significantly lower material costs. Considering
SFRC along bottom surface to resist bending cracks

SFRC along front edge to increase robustness against missing bedding

SFRC at longitudinal joint to avoid chipping

PC in less critical areas; at core and at outer surface

Figure 6.1: Proposed segment design consisting of a plain concrete (PC) “core” poured within an SFRC “tub.”

Figure 6.2: Proposed segment design consisting of a standard reinforced concrete segment in which the splitting reinforcement at the longitudinal joint is replaced with an SFRC “wedge.”

the investigations performed within this work such a segment may be a segment that has a SFRC along all of the segment edges, with PC core, such as that shown in Figure 6.2. Such a segment is imbued with almost all the positive effects of SFRC, with significantly lower material costs. The SFRC at the longitudinal joint resists chipping at segment corners and the SFRC along the bottom of the segment resists bending cracks along the inner diameter of a segment. The SFRC layer along the outer edge of the sample does not provide much additional reinforcement against jack forces, however it provides significant reinforcement against possible imperfections, such as the potential lack of segment bedding during thrust force application upon machine advance. SFRC may not be necessary on the outer layers of the lining due to the confining effects of the grout layer. Such a segment may, however, be difficult to produce, as the SFRC and PC must be cast in two
distinct casting phases. Alternatively, the simplest modification to existing segment designs is to forgo the reinforcement placed beneath the longitudinal joint to counteract splitting stresses with an SFRC “wedge” placed at the corners of the segment. The major advantage of this design is that no significant change to the casting process must be made, with the exception of pouring an SFRC layer first. The vibration of the mold during the casting procedure should be sufficient to force the SFRC to slip to the edges of the segment and to create the intended reinforcement shape.

In conclusion, the research presented in this thesis strongly supports the adoption of steel fibers as a reinforcement scheme for tunnel linings. Steel fibers not only provide improved crack control over standard RC structures, but are able to sustain significantly higher loadings than conventional design methods predict. Design of SFRC structures remains, however, a significant issue. Unless non-linear techniques for structural analysis of SFRC structures become accepted as standard design methods, it may be that the full potential of SFRC as a building material remains unrealized. If, on the other hand, numerical techniques such as those presented in this thesis become accepted within the civil engineering community, SFRC linings may soon become the standard choice for tunnel lining design worldwide.