Optimization of input parameters for material model of fibre reinforced concrete and application on the numerical simulation of tunnel lining

Tereza Sajdlová, Radomír Pukl

Červenka Consulting, Prague, Czech Republic.

Abstract

Nonlinear finite element simulation has a big potential in the field of fibre reinforced (FRC) structures. Special material models accounting for the high toughness and ductility are available for modeling of FRC-material. Input material parameters for the numerical models are here of crucial importance. They are identified from measured response of four-point bending beams using inverse analysis. The optimal material input data sets are utilized for nonlinear modeling of segmental tunnel lining. Utilization of steel fibre reinforced concrete (SFRC) for segmental tunnel lining promises potential advantages in comparison to the traditionally reinforced concrete (RC) structures - faster manufacturing, lower risk of corrosion, less damage during transport. Results from the experimental and numerical investigations for RC and SFRC segments are presented. Response of the structural members under service loads and their damage under limit loads are evaluated in order to check and confirm suitability of the SFRC segments for practical utilization.

Keywords

FE analysis, segmental tunnel lining, fibre reinforced concrete, non-linear material models, identification of material parameters.

1 Introduction

Steel fibre reinforced concrete (SFRC) is a promising material for application in precast concrete tunnel lining segments installed by TBM (tunnel boring machine) during tunnel excavation. Full size laboratory tests of both RC and SFRC segments have been performed in order to check their resistance under various loading conditions, representing selected critical states during installation, and in the final structure.

The tests were accompanied by an extensive numerical study using nonlinear computer simulation. The nonlinear finite element simulation is recently a well-established approach for analysis of reinforced concrete structures and it has a big potential also in the field of fibre reinforced concrete (FRC) structures. Special material models at macroscopic level are available for modelling of FRC-material in the numerical simulation of FRC-based structures, taking into account higher ductility of FRC. This can be represented by larger fracture energy in the material models. Appropriate input material parameters for these numerical models are basic precondition for successful analysis of the FRC structures. Requested values, in particular the tensile material properties, can be identified using inverse analysis method from results of available tests on simple structures such as bending beams.

2 Testing program and numerical models

Laboratory tests were performed in the Klokner Institute of CTU for both RC and SFRC segments in several configurations representing selected design conditions (Figure 1). They are labeled as "vault bending" (A), "lateral pressure" (B) and "lateral bending" (C). Numerical simulations, employing finite element technology with non-linear material models for concrete, were performed in order to obtain structural response, propagation of damage and failure. Some of the simulations have been made in advance in order to adjust boundary conditions for the tests such as expected failure forces or support stiffness.

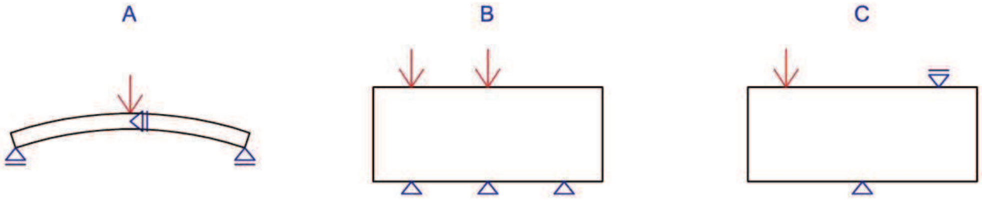


Figure 1: Scheme of laboratory tests

3 Nonlinear material models for fibre reinforced concrete

Special constitutive material models have been developed for description of FRC-material in the nonlinear finite element analysis (Červenka (2011), Pukl et al. (2005)). They account for the high toughness and ductility of FRC, as well as other properties differing FRC material from conventional plain concrete (e.g. shape of the descending branch of the crack opening law). Several levels of FRC modelling at the material levels are available for performing the nonlinear numerical analysis. The first choice could be utilization of the material models developed for the plain concrete with appropriately adjusted material parameters (tensile strength, fracture energy). The shape of the tensile descending branch is in this case an exponential function, which is not optimal for the description of FRC response, but its use is rather pragmatic – it is of advantage that the models for plain concrete are very well verified and exhibit rather stable behaviour.

In order to improve modelling of the FRC tensile behaviour material laws with special forms of the tensile descending branch more suitable for FRC were formulated and implemented. They are derived from plane stress material law for plain concrete. If the fracture energy is known, an objective material law based on the crack band approach can be used. After cracking, the tensile stress drops to certain fraction of the tensile strength. In practical cases the fracture energy value is often difficult to evaluate since in the tests it is a hard task to follow the long-persisting descending branch until the zero tensile stress. In such a case a local formulation of the tensile material law is available. It is similar to the previous model but it is formulated directly in terms of strains and does not employ the fracture energy and crack band approach.

The most sophisticated and most general model of FRC material represents an extension to the fracture-plastic constitutive law called CC3-User model. It describes the tensile behaviour according to the material response measured in tests point-wise in terms of the stress-strain relationship. The first part of the diagram is the usual stress-strain constitutive law. After exceeding the localization strain the material law assumed for the prescribed characteristic crack band width is adjusted to the actual crack band width. The FRC material can be in the numerical models also combined with the conventional reinforcement.

4 Inverse analysis of SFRC material parameters

A set of four-point bending tests was used for inverse analysis. The tested beams were casted from concrete C55/67 with fibres of length 60 mm and diameter 0.8 mm in amount of 40 kg/m^3. The scheme and dimensions of the tested and simulated specimen is shown in Figure 2. Finite element model of the four point bending beam created in ATENA 2D shows Figure 3. Load-deflection diagrams from the performed tests have been documented in Smiřinský (2012). The basic material parameters were generated in ATENA from the mean compressive strength of 74 MPa which is based on the characteristic cubic compressive strength of concrete C55/67. The generated material parameters are summarized in Table 1.

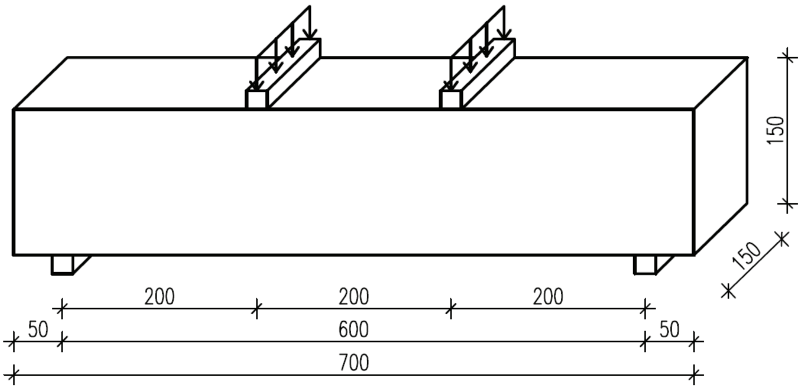


Figure 2: Scheme of the four-point bending test

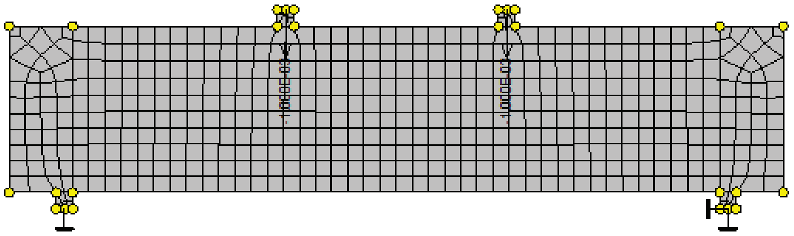


Figure 3: Numerical model of the FRC beam in ATENA 2D with finite element mesh

Table 1: Generated material parameters for plain concrete C55/67

Material model	E [MPa]	μ [-]	ft [MPa]	fc [MPa]	Gf [N/m]	wd [m]	RC [-]
3D NLC2	38000	0.2	4.2	-63	106	-0.0005	0.2

In the next step, the material input parameters were randomized using advanced probabilistic system SARA. Regular stochastic distributions with the mean values corresponding to the adjusted ones have been used for selected material parameters. The results from the stochastic analysis were compared with the measured response for the specimens made with the fibre contents of 40 kg/m^3, and the optimal sets of material parameters have been derived (Table 2).

Table 2: Identified material parameters of fibre reinforced concrete with 40 kg/m^3 of fibres

Material model	E [MPa]	μ [-]	ft [MPa]	fc [MPa]	Gf [N/m]	wd [m]	RC [-]
3D NLC2	38000	0.2	2.15	-63	2700	-0.0125	1
3D NLC2 User	38000	0.2	4.23	-63	-	-	1

The relationship between the material input parameters and fibre contents has been determined. The multiplicative factor for the fracture energy of the plain concrete is 25 for the FRC with the fibre contents of 40 kg/m^3. For the tensile strength this factor is 0.5 in the model 3D NLC2. Note that the resulting material parameters for fibre reinforced concrete do not necessarily represent the real material properties but rather just appropriate input parameters for the numerical material model of FRC material.

Similar procedure with comparable results has been performed using neural network adaptive system for automatic adjustment of the optimal set of input material parameters. Another level of approach is combination of the basic models for plain concrete with smeared reinforcement representing the steel fibres, including their bond properties to the concrete. Stochastic procedures based on random variables and random fields technologies are employed in order to account for random distribution of the steel fibres. This kind of FRC modelling is recently under progress and development.

Load-displacement diagrams of FRC beams from numerical simulations using various material models are compared with the measured ones in Figure 4. It shows very good agreement between the laboratory tests and their numerical simulation.

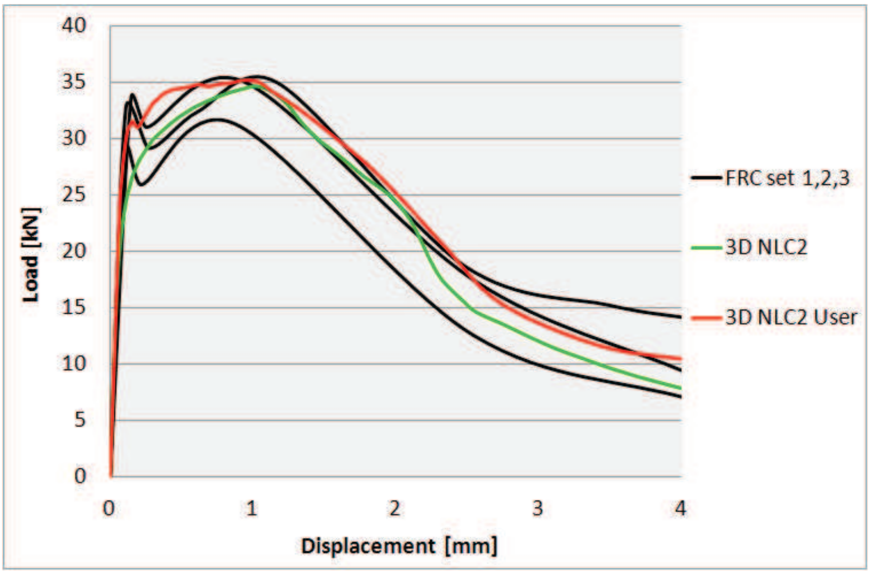


Figure 4: Comparison of load-deflection diagrams for FRC with fibre contents of 40 kg/m^3

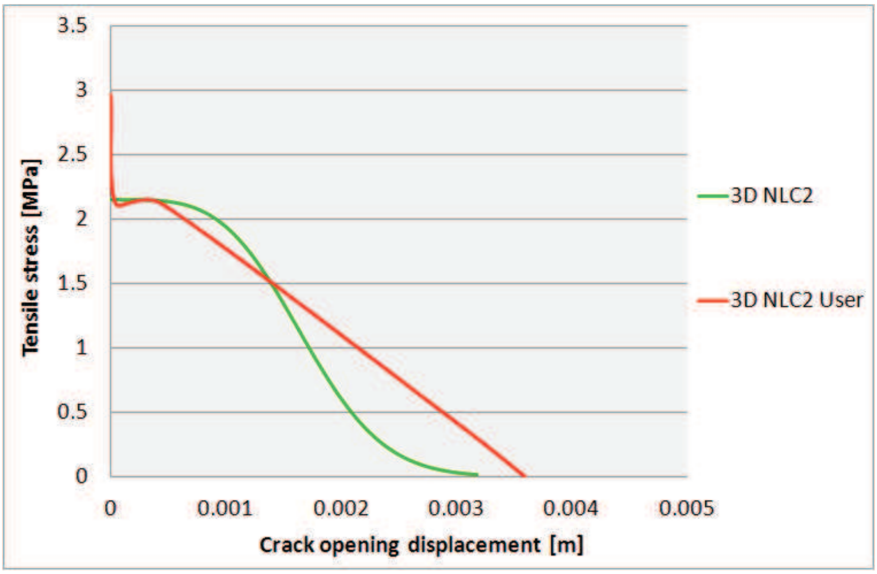


Figure 5: Crack opening law for FRC with fibre contents of 40 kg/m^3

5 Vault bending tests

Subject of this experiment was to clarify behaviour of the segment under local lateral load, in particular in case of SFRC segment. The test setup in the laboratory of Klokner institute can be seen in Figure 6. Load-deflection diagrams from two tests of SFRC segments are the black (dark) lines in Figure 6. Numerical model using material model derived in previous chapter was created in ATENA 3D Engineering according to the original design. The load-displacement diagram from numerical analysis of the SFRC segment is shown in Figure 7 (labelled "3D model") and compared to the experimental ones. The numerically obtained ultimate load carrying capacity of 113 kN is equal to the measured capacity of the experiment No. 1; all the response curves have the same character.

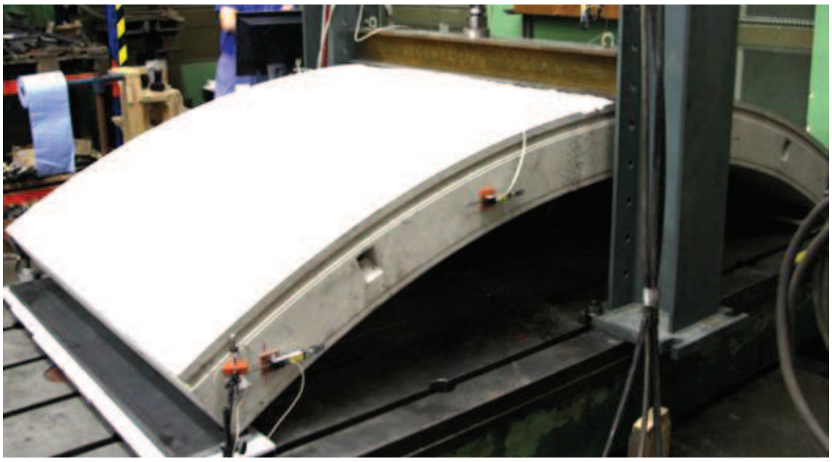


Figure 6: Vault bending: Laboratory tests setup

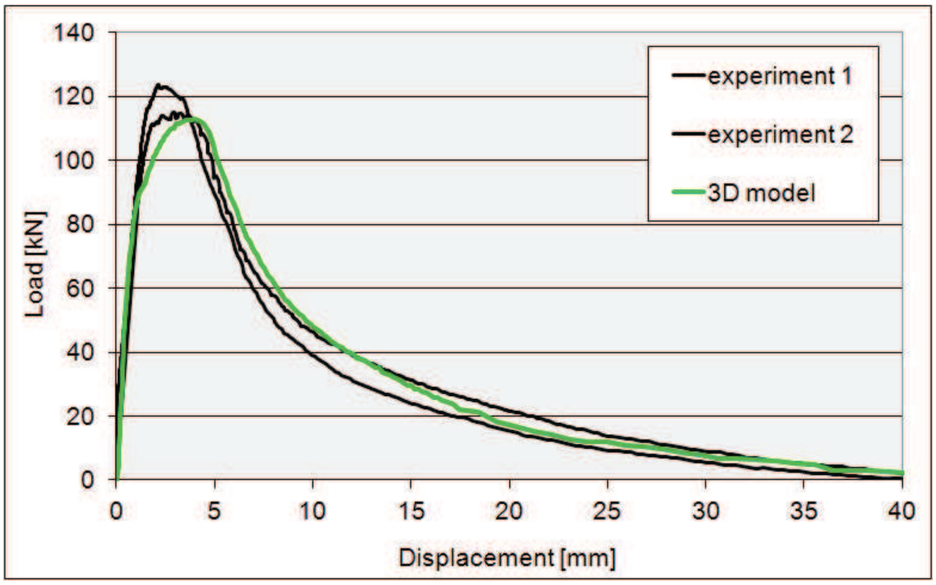
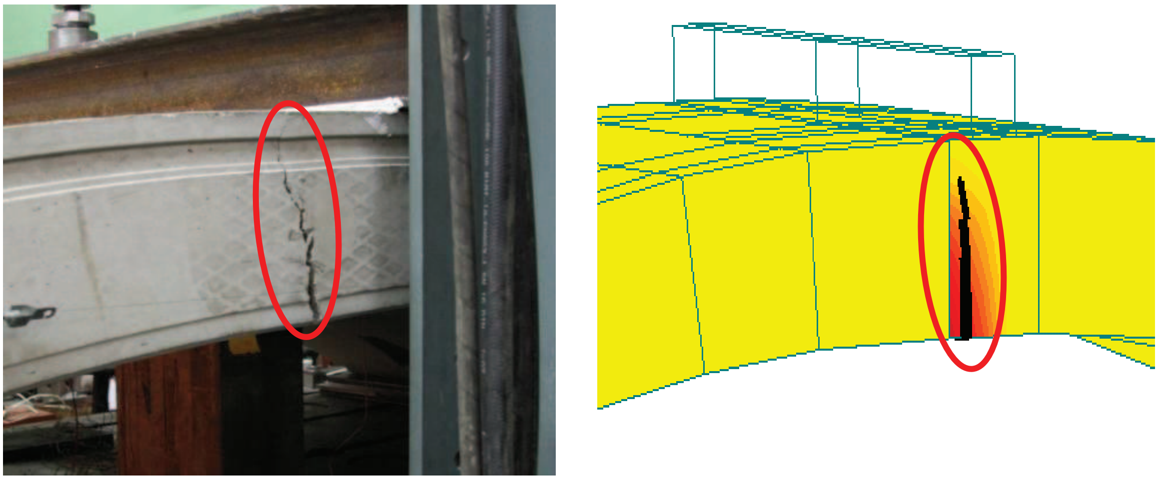


Figure 7: Vault bending: Comparison of LD diagrams for SFRC segments - experiment vs. numerical model

Development of bending cracks in the model was very close to the structural behaviour in experiment. Compare the final crack in Figure 8 (b) with the crack from experiment (Figure 8 (a)); the significant cracking areas are marked. The cracks in both experiment and numerical analysis are here strongly localized even in the SFRC material.



(a) Experiment *(b) Numerical simulation*

Figure 8: Comparison of cracks in SFRC segment – vault bending

6 Lateral pressure

This test simulates action of the TBM machine press devices during installation and assembly of segments. The laboratory tests and numerical simulations were performed for RC segments (comparison of resulting failure crack pattern see Figure 9) as well as for SFRC segments. The model of SFRC segment shows higher number of cracks (crack band) with smaller width (Figure 11). The calculated capacity of SFRC segments is slightly higher than the capacity of RC segment, and the failure regime is more ductile.

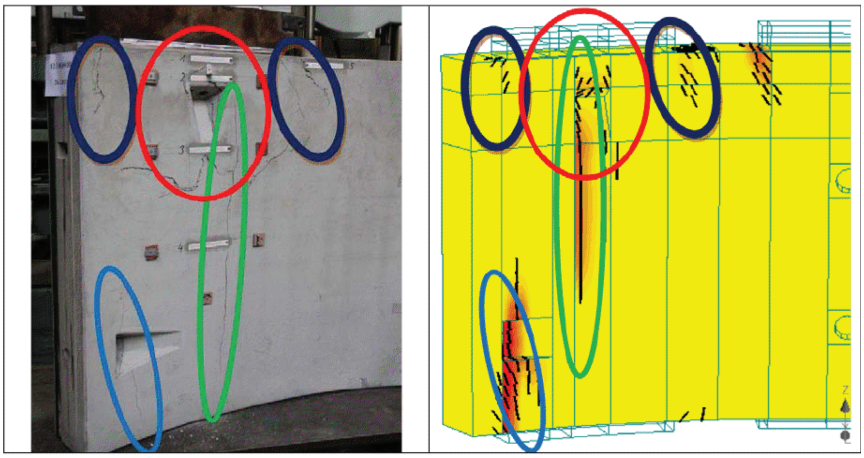


Figure 9: Laboratory test (left) and FE model (right) of RC segment – location of principal cracks

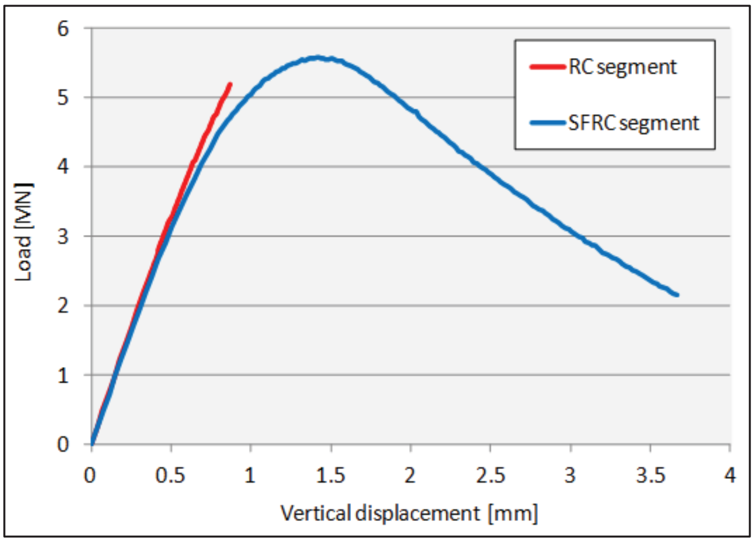


Figure 10: Lateral pressure: Comparison of LD diagrams for RC and SFRC segment

7 Comparison of RC and SFRC in tunnel segments

The RC segments have a clear advantage, that they can be reinforced relatively strongly in the direction where tensile forces appear. Segments made of SFRC are not capable to resist the increasing tensile stress when it is necessary. On the other hand, the fibre reinforcement has technological advantages and may bring savings in production of segments. Another advantage of segments made from SFRC lies also in lower sensitivity to local damages during assembly of the lining. It is necessary to take into account the design conditions in the underground space, which provide the geotechnical loading including the underground water pressure. The other loadings given by construction technology (production, transport and assembly of segments) may define other unfavorable loadings. If all these factors are taken into account, it is a moment for decision if segments made of SFRC may be designed or if the bar reinforcement is necessary.

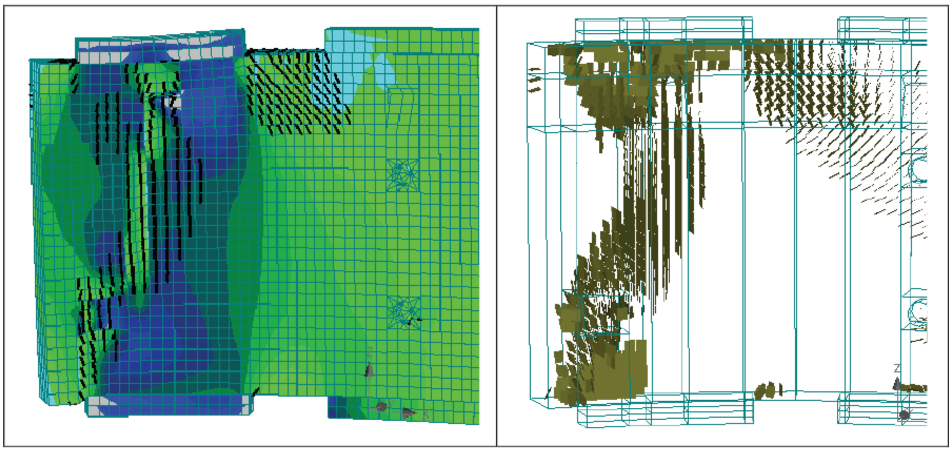


Figure 11: Cracks in SFRC segment model

8 Conclusions

Testing and numerical modeling of RC and SFRC has been performed in order to check their performance in selected critical design and loading situations. It has been proved that using of SFRC for production of tunnel segments is a prospective option. The numerical models successfully predicted and accompanied the laboratory tests; in the numerical model a more detailed evaluation of structural response is available compared to experiments. Advanced material models for numerical simulation of fibre reinforced concrete are available, but determining appropriate input material parameters suitable for realistic analysis lies above the usual testing methods. Inverse analysis is a feasible way to identify optimal set of input parameters for modelling the fibre reinforced concrete material and structures. Possible future utilization of the SFRC tunnel segments in the Czech Republic was successfully confirmed by construction of the 15 m long test section in the Prague metro line A extension.

9 Acknowledgement

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10 References

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