HEAT TRANSFER ANALYSIS OF BONDED ANCHORS IN SOLID AND PERFORATED CALCIUM SILICATE MASONRY STONES

THERMISCHE ANALYSE VON VERBUNDDÜBELN IN KALKSAND-VOLL- UND -LOCHSTEINEN

Sebastian Geiger, Hitesh Lakhani, Jan Hofmann

Institute of Construction Materials, University of Stuttgart

SUMMARY

The present paper deals with the first step for evaluating the performance of bonded anchors installed in calcium silicate masonry stones during fire i.e., to carry out a transient heat transfer analysis. The current study focuses on two aspects: 1) the importance of modelling the heat transfer within the cavity/perforations of the calcium silicate stone and 2) the influence of mortar layer on the predicted temperature along the anchor rod. The heat transfer scenarios investigated are air-filled cavity and cavity radiation, resp. It has been shown that it is important to consider the radiation heat transfer in stone cavities. The numerical studies were performed using ANSYS®, on two different geometries of perforated calcium silicate stone and a reference solid stone.

ZUSAMMENFASSUNG

Der vorliegende Beitrag befasst sich mit dem ersten Verfahrensschritt zur Beurteilung des Verhaltens von Verbunddübeln im Brandfall, die in Kalksandsteinmauerwerk eingebaut sind, d. h., es wird eine instationäre Wärmeübertragungsanalyse durchgeführt. Die vorliegende Studie konzentriert sich auf zwei Aspekte: 1) Die Notwendigkeit der Modellierung der Wärmeübertragung innerhalb des Hohlraums des Kalksandlochsteins; 2). Dem Einfluss der Mörtelschicht auf die vorhergesagte Temperatur entlang der Ankerstange.

Die untersuchten Wärmeübertragungsszenarien sind luftgefüllter Hohlraum und Hohlraumstrahlung. Es hat sich herausgestellt, dass es wichtig ist, die Strahlungswärmeübertragung in steinernen Hohlräumen zu berücksichtigen. Die numerischen Studien wurden mit ANSYS® mit zwei verschiedenen Kalksandlochsteinen und einem Kalksandvollstein durchgeführt.

1. INTRODUCTION

Over the year the behaviour of bonded anchors in concrete members during fire have been studied experimentally and numerically by many researchers [1–5]. But its behaviour in masonry has been seldom investigated [6]. Due to the large variety of masonry bricks/stones/units available in the market, it is difficult to have a general fire resistance qualification of bonded anchors in masonry. Hence, the qualification must be associated with a tested masonry stone with a geometric configuration. The use of calibrated Finite Element (FE) simulations in augmentation with the experimental investigation can provide an economical solution, to qualify the bonded anchor in masonry units.

In general, the process of determining the fire resistance (numerically) involves two steps:

1. Conducting a transient heat transfer analysis to determine the spatial and temporal distribution of temperature.
2. Conducting a thermal stress analysis using the temperatures computed in step 1.

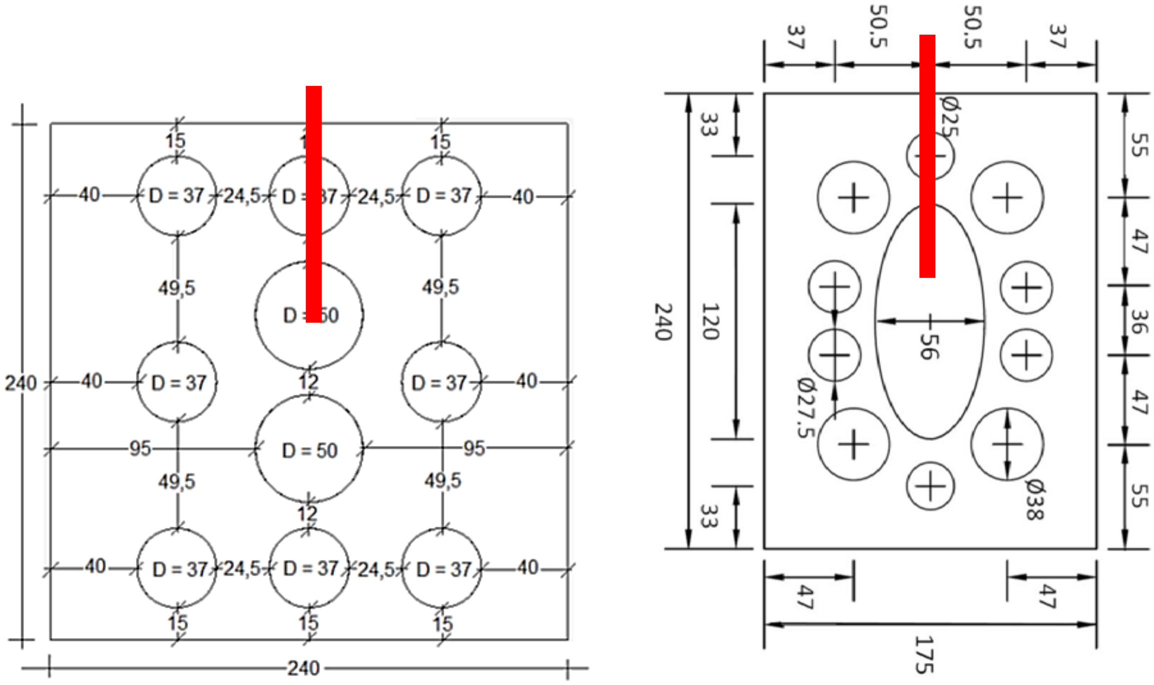
The step 1 forms the theme of this paper. The transient heat transfer analysis is highly nonlinear due to the nonlinear thermal boundary conditions (heat transfer from hot gases/fire to the surface via convection and radiation) and temperature dependent thermal properties. In case of bonded anchors installed in masonry the problem becomes more complex due to the presence of cavities/perforations in the masonry stone. Hence, to simply the problem various assumptions could be made regarding the heat transfer/flow within the perforations/cavities. For example, for the numerical studies conducted by Reichert and Thiele (2019) [6], it was assumed that the cavity of the masonry stone is filled with air and the heat transfer primarily takes please via conduction. Another possible more realistic and complex way of modelling the heat transfer within the cavity would be via radiation.

The paper presents the numerical studies performed using general purpose FE program ANSYS® [7], to compare the effect of the above mentioned two possible ways of modelling heat transfer in cavity, on the predicted temperatures along the anchor rod. For the numerical studies two different perforated calcium silicate stones referred as KSL-1 & KSL-2, were selected. Simulations were also performed for a reference solid calcium silicate stone (VS) to compare with the perforated stones. Furthermore, the influence of mortar layer on the predicted temperature along the anchor rod is also presented.

2. MODELLING APPROACH

The 3D transient heat transfer analysis is performed using general purpose FE software ANSYS® [7]. The dimension of the calcium silicate stones selected for the study are given below and the cross-sectional details of KSL-1 & KSL-2 are shown in Fig. 1.

1. KSL-1: 240 mm × 240 mm × 112 mm
2. KSL-2: 175 mm × 240 mm × 113 mm
3. VS: 240 mm × 240 mm × 112 mm



(a) KSL-1 *(b) KSL-2*

Fig. 1: Geometric details of perforated calcium silicate stones (All dimensions in mm)

The stones KSL-1 and VS were modelled with a bonded anchor consisting of M12 threaded rod with a total length of 135 mm (85 mm anchorage length + 50 mm projection) and 2 mm thick mortar layer (16 mm hole diameter). The anchor in KSL-2 also consisted of M12 anchor rod but with total length of 150 mm (100 mm anchorage length + 50 mm projection). It can be seen from Fig. 1(a) and 1(b) that both the anchor passes through two cavities. In practice sieve sleeve of 16mm diameter would be used to install the anchor but for modelling the sleeve was neglected. Alternatively, a 2 mm mortar layer as shown in Fig. 2, was modelled along the anchorage length to study its effect on predicted temperatures.

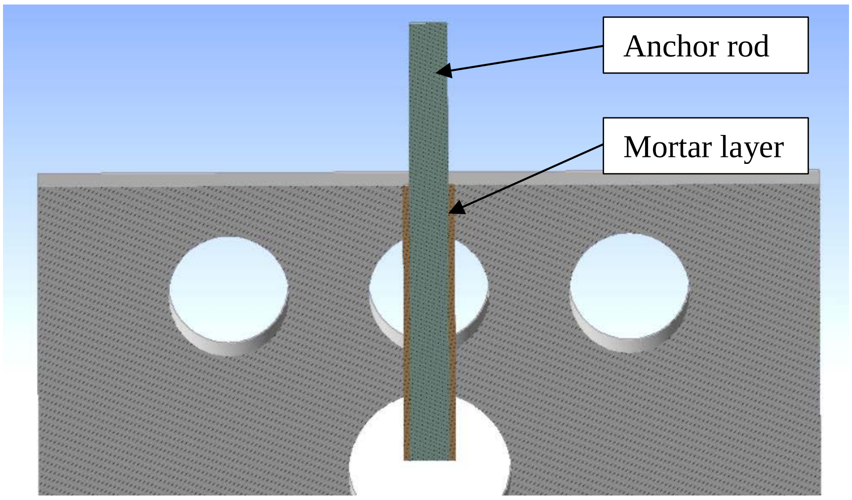
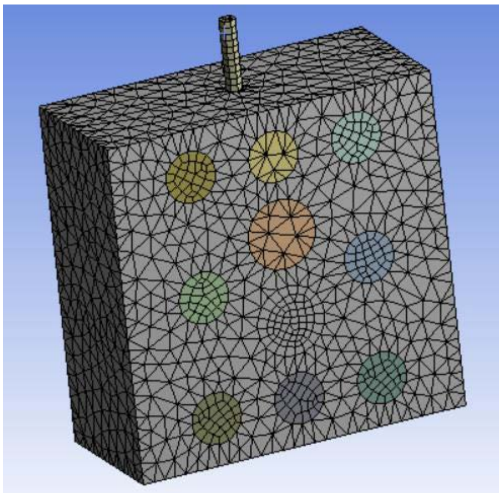
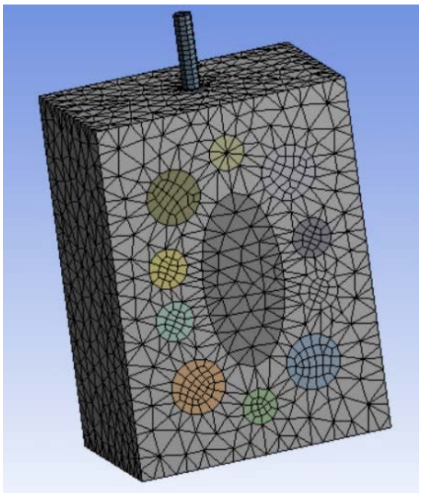


Fig. 2: Geometric model of anchor rod and mortar layer

The geometric discretization (FE mesh) for KSL-1 & KSL-2 is shown in Fig. 3. It should be noted that the models were created such that different solids representing the cavity could be activated/deactivated to simulate different heat transfer scenarios in the cavity, while using the same FE mesh. Taking advantage of this functionality no separate model was created for VS, but all solids were assigned the properties of calcium silicate to simulate VS.



(a) KSL-1



(b) KSL-2

Fig. 3: FE Mesh for stones KSL-1 & KSL-2

2.1 THERMAL BOUNDARY CONDITIONS

The fire exposure is defined by the standard temperature-time curve defined by ISO834 [8]. The face of stone on which the anchor is installed is exposed to fire and all other faces are assumed to be insulated. Hence, the exposed face was assigned radiative (with emissivity = 0.7) and convective boundary conditions (with convection coefficient = 25 W/m^2 K) to simulate the heat transfer from the hot gases/fire to the surface. The thermal boundary conditions are demonstrated in Fig. 4.

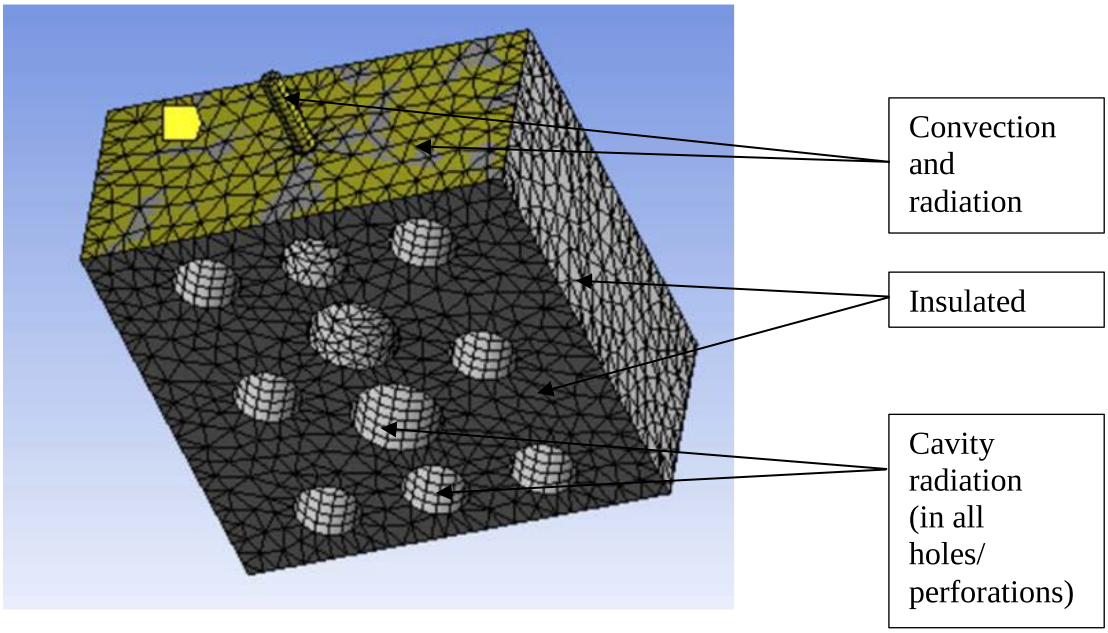


Fig. 4: Applied thermal boundary conditions

2.2 THERMAL PROPERTIES

The temperature dependent thermal properties (thermal conductivity and specific heat) for anchor rod and calcium silicate masonry stones were taken from EN1993-1-2 [9] & EN1996-1-2 [10] respectively and are also shown in Figs. 5 & 6.

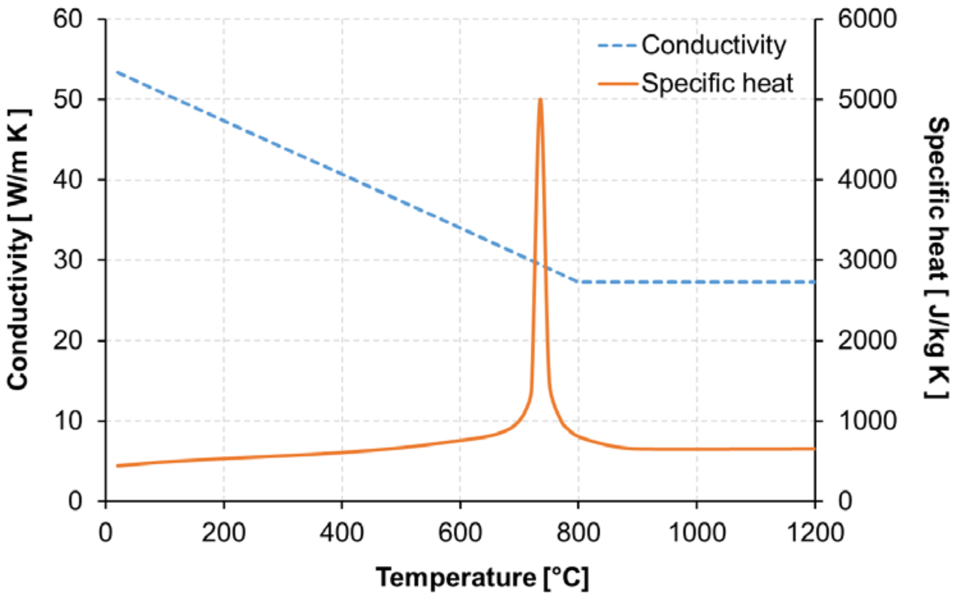


Fig. 5: Variation of thermal properties with temperature for anchor rod

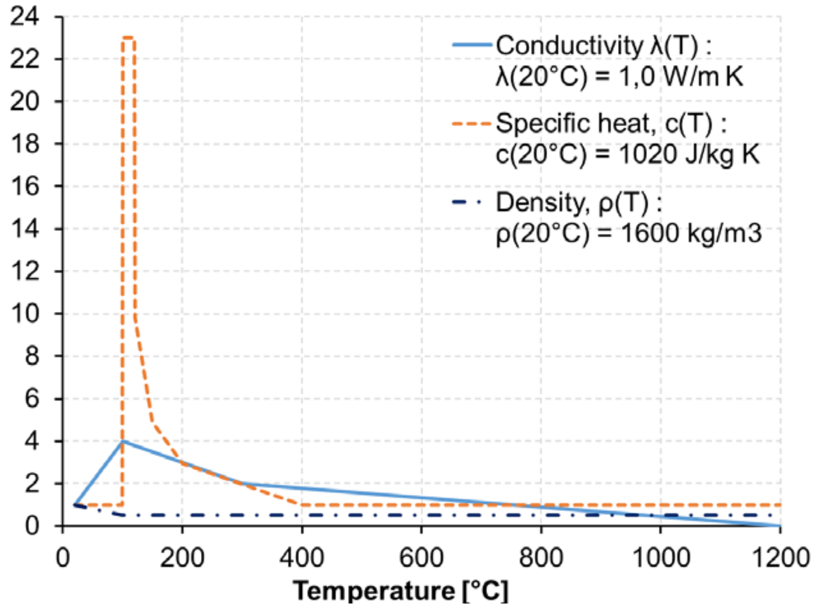


Fig. 6: Variation of thermal properties with temperature for calcium silicate masonry units, normalized with respect to 20°C value

In absence of any data available for the thermal properties of mortar, it was assumed that its thermal properties are similar to those of concrete specified by EN1992-1-2 [11]. For the cases where the cavities were assumed to be filled with air as assumed by Reichert and Thiele (2019) [6], following temperature independent properties were used: Density = 1.1614 kg/m^3; Specific heat = 1007 J/kg K and thermal conductivity = 0.026 W/m K.

3. RESULTS AND DISCUSSION

To discuss the results, the following nomenclature has been used:

1. *KSL-1*, *KSL-2* and *VS* are used to refer to various stones.
2. *MM* & *OM* are used to identify the cases with and without mortar layer, respectively.
3. *L* & *S* are used to identify the heat transfer scenario in cavity air filled and cavity radiation, respectively.

3.1 HEAT TRANFER SCENARIO IN CAVITY

Simulations with radiation and air in the cavities of the KSL-1 and KSL-2 were simulated. The simulation results are presented as temperature variation along the anchor rod. All the results presented in this section are for models with 2 mm mortar layer.

The simulation results for KSL-1 are shown in Fig. 7. In this case the influence of the heat transfer scenario in the cavity was found to be insignificant for shorter exposure duration of 30 minutes. But the predicted temperatures with heat transfer scenario "*S*" were always slightly lower as compared to case "*L*" and this difference is found to increase with time. The maximum temperature difference observed along the length of anchor rod in 1st cavity & 2nd cavity were 40°C and 49°C (lower for case "*S*"). The reason for this behaviour lies in the fact that for case "*L*" the heat transfer mode is conduction through air, which is very slow, thus giving an insulating effect. This insulating effect prevents any heat loss from the anchor rod, thus results in heat accumulation and flat temperature profile in 2nd cavity. It should also be noted that the flat temperature profile in 2nd cavity at 30 minutes for case "*S*" is because of the lower temperature attained at the end of the anchor rod. These lower temperature in-turn results in relatively low radiative heat transfer/exchange between mortar surface & cavity wall and the cavity walls themselves.

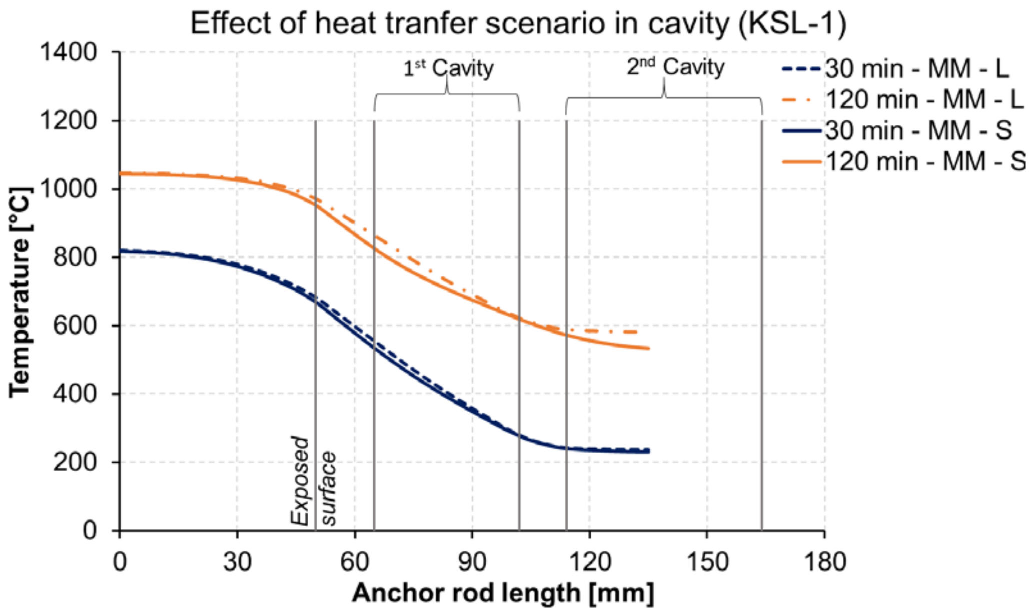


Fig. 7: Effect of heat transfer scenario in cavity for KSL-1

On comparing the temperature profiles along anchor rod for the same anchor in VS and KSL-1, shown in Fig. 8. It can be concluded that the presence of cavities in stones would have negative influence on the load capacity of bonded anchors. Since the temperature profile along the anchor rod in always & significantly higher in perforated stone as compared to solid stone. In case of solid brick (VS) the temperatures are lower along the anchor rod due to longer bonded length which makes a direct heat exchange between anchor rod and substrate possible.

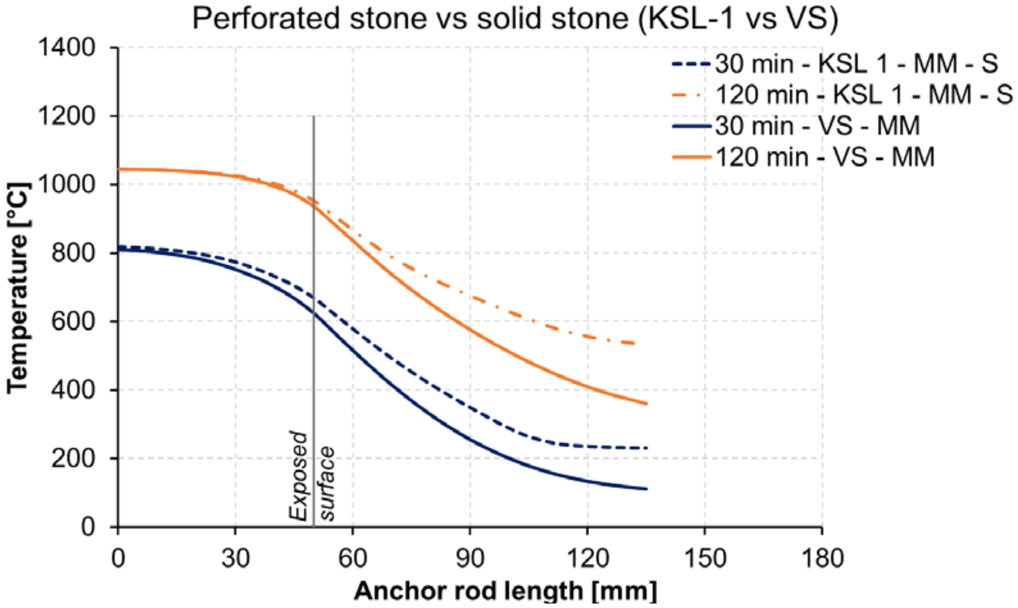


Fig. 8: Temperature comparison between KSL-1 and VS

Fig. 9 shows the results for KSL-2. For a fire exposure time of 30 minutes, the temperature curves are almost identical, which is in line with the observations made for KSL-1. The longer the duration of the fire exposure, the clearer is the differences between the different heat transfer scenarios. Since the anchor rod ends in a cavity, an insulation effect due to the air-filled cavity makes the temperature curve to run at a constant temperature until the end of the anchor rod. The reason for such behaviour is the same as explained for KSL-1. In case of KSL-2 the effect of cavity radiation "*S*" is more significant due to the (narrow) shape and the (larger) size of the 2nd cavity in which the anchor rod ends.

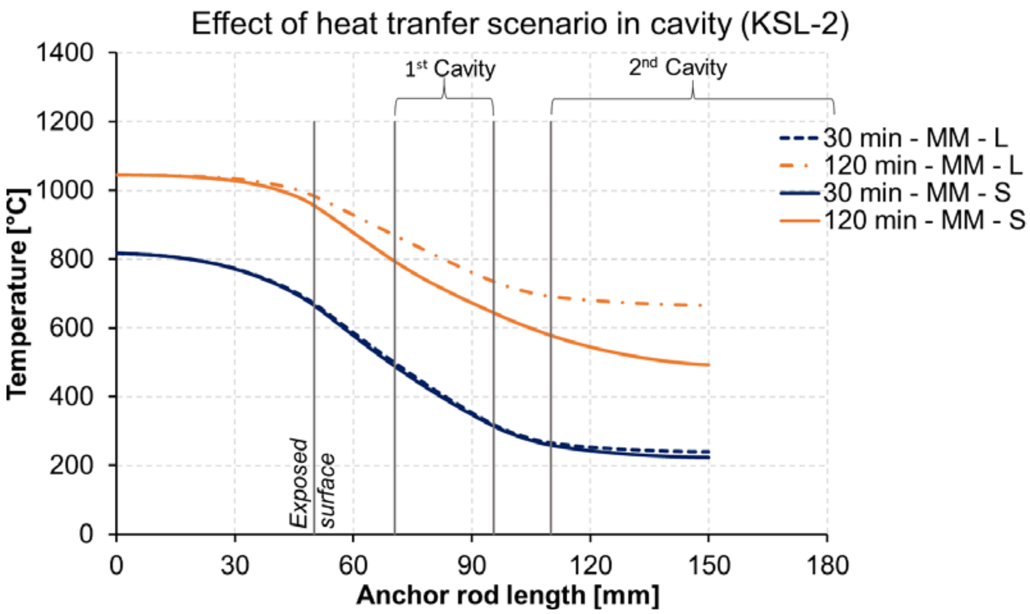


Fig. 9: Effect of heat transfer scenario in cavity for KSL-2

To further illustrate the importance of cavity radiation "*S*" further numerical simulations were performed on KSL-2. The results of these simulations are given in Fig. 10. Here, the temperature profiles are shown for radiation (S), air (L), radiation in the first cavity and air in the second (SL), and air in the first cavity and radiation in the second cavity (LS). Only the two points in time 30 min and 120 min are shown to keep the diagram clearer.

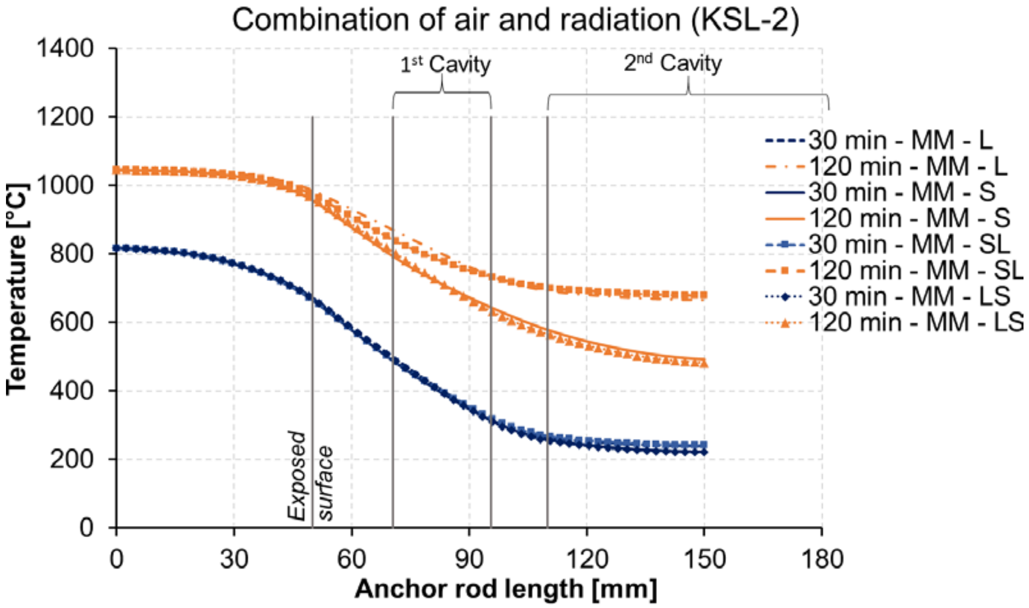


Fig. 10: Air (L), radiation(R) & combination (SL; LS) in KSL-2

It can be seen from Fig. 10 that the modelling of the heat transfer in the second cavity significantly influences the temperature profile. If one considers the case of air (L) and the case of radiation in the first cavity & air in the second cavity (SL), then these two temperature curves are very similar. In the same way, if one compares the two temperature curves fore cases radiation (S) and air in the first cavity & radiation in the second cavity (LS), then these also run very close together. The simulation scenario in the first cavity thus has only a minimal influence on the temperature curve. Consequently, the cavity scenario in the second cavity is the decisive one for the entire temperature profile along the anchor rod.

3.2 INFLUENCE OF MORTAR LAYER

The numerical investigations regarding the necessity to model the mortar layer were carried out on all three masonry units KSL-1, KSL-2 and VS. Here, mortar layers of 2 mm thickness were simulated. It can be seen from the simulation results Figs. 11 and 12 that the mortar layer has insignificant influence on the predicted temperature. This is explained by the fact that the mortar layer is too thin to have a noticeable influence on the system. In addition, investigations were made with thicker mortar layers. These results also confirmed the results of the presented simulation results. It can therefore be assumed that the modelling of the mortar layer is not necessary in the numerical investigations.

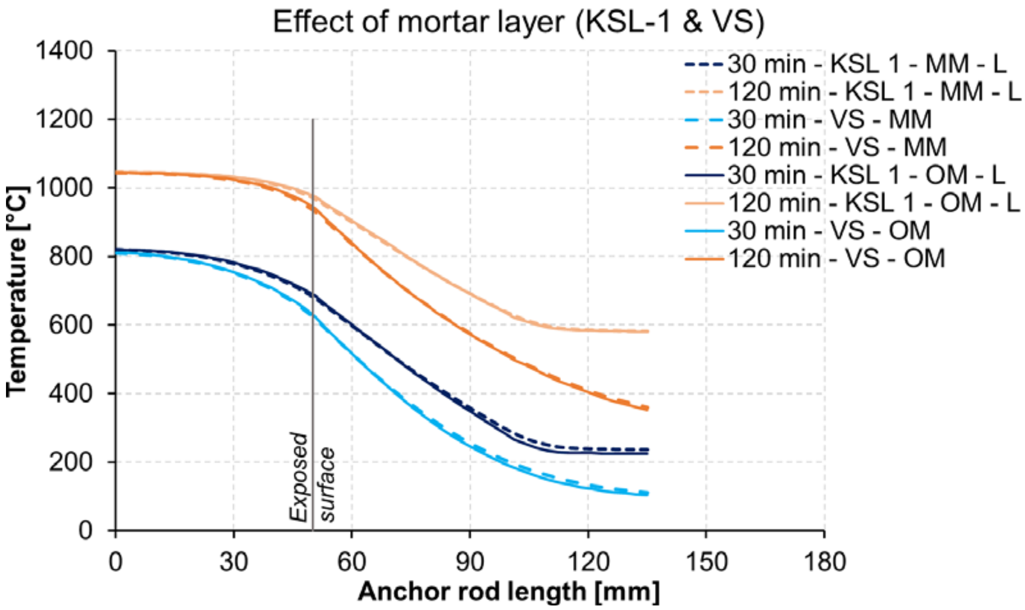


Fig. 11: Results for KSL-1 and VS for simulations with and without mortar layer

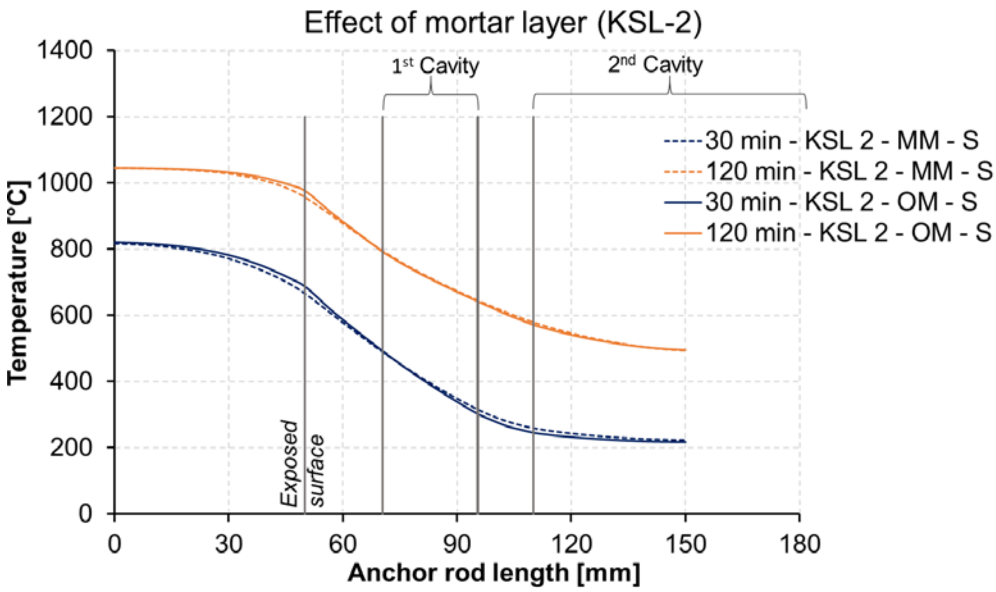


Fig. 12: Results for KSL-2 for simulations with and without mortar layer

4. CONCLUDING REMARKS

The investigations show that the greatest influence on the temperature curve comes from the last cavity. In the case when cavity radiation is simulated, heat is transferred from the upper area of the cavities to the lower areas, which in turn has a cooling effect on the upper areas and thus reduces the anchor rod temperature.

Since the temperature differences at the anchor rod surface are nevertheless not very high between the different simulated heat transfer scenarios up to the typical critical temperature around 340°C, the simplified variant with air may be used. Nevertheless, it is recommended to consider the more realistic cavity radiation for simulations.

From the investigations in which the influence of the mortar layer on the temperature profile along the anchor rod was made, it can be concluded that the mortar layer has no influence on the temperature course. Thus, the mortar layer can be neglected in the FE model for investigating the bonded anchors in masonry under fire load.

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