Experimental investigation on spalling mechanisms in heated concrete

M. Zeiml[1] and R. Lackner[1,2]
[1] *Institute for Mechanics of Materials and Structures, Vienna University of Technology, Vienna, Austria*
[2] *Computational Mechanics, Technical University of Munich, Munich, Germany*

ABSTRACT: Some recent results obtained during an experimental campaign on concrete spalling in fire conditions are presented in this paper. Since spalling was visually recorded by means of a high-speed camera, the slow-motion sequences provided an insight into the size, shape, and velocity of the spalled-off pieces which made it possible to evaluate the released energy during the acceleration of the concrete chips and to clarify the causes of spalling. The two commonly-accepted theories about the causes of concrete spalling are also recalled, taking advantage of the test results. The roles of the various thermal, mechanical and hydral processes controlling concrete spalling are discussed.

1 INTRODUCTION

In case of fire loading, concrete structures are affected by various physical, chemical, and mechanical processes, leading to degradation of the material parameters of concrete and spalling of near-surface concrete layers. Especially in case of tunnel fires, with the thermal load characterized by a steep temperature increase during the first minutes of the fire and a maximum temperature exceeding 1200°C, spalling significantly reduces the load-carrying capacity of the structure. In the literature, different types of concrete spalling due to fire loading are defined (Kalifa et al. 2000; Schneider and Horvath 2002; Hertz 2003; Khoury and Majorana 2003). Depending on its origin, spalling can be divided into

1. aggregate spalling (splitting of aggregates),
2. corner spalling (i.e., corners of columns or beams fall off), and
3. surface spalling (surface layers of concrete fall off or burst out of the structural element).

Moreover, depending on the underlying physical mechanisms, spalling can be divided into

1. progressive spalling (or sloughing-off, where concrete pieces fall out of the structural element) and
2. explosive spalling (violent burst-out of concrete pieces characterized by sudden release of energy).

Two phenomena are considered to be the main causes for spalling. On the one hand, restrained thermal dilation results in biaxial compressive stresses parallel to the heated surface which lead to tensile stresses in the perpendicular direction (Bažant 1997; Ulm et al. 1999). This type of spalling in consequence of thermo-mechanical processes can be referred to as thermal-stress spalling (Khoury and Majorana 2003; Khoury 2006). On the other hand, the build-up of pore pressure in consequence of vaporization of water (thermo-hydral processes) results in tensile loading of the microstructure of concrete (Meyer-Ottens 1972; Anderberg 1997; Consolazio et al. 1997; Kalifa et al. 2000; Schneider and Horvath 2002; Hertz 2003), which can be referred to as pore-pressure spalling (Khoury and Majorana 2003; Khoury 2006).

In this paper, results of recently-conducted fire experiments are presented where spalling was recorded visually by means of a high-speed camera. The recorded images and sequences are used to investigate the velocity of the spalled-off pieces, yielding estimates for the released energy, and to highlight the processes responsible for spalling and their respective influence.

2 SPALLING EXPERIMENTS

Within the underlying fire experiments, reinforced concrete slabs with the dimensions 0.60 × 0.50 × 0.12 m made of concrete C30/37 and C60/75 (water/cement-ratios of *w/c* = 0.35 and 0.55, respectively; limestone aggregates) were subjected to fire loading. In selected batches, air-entraining agents and/or polypropylene (PP) fibers were added to the mix design. The PP-fibers (18 μm in diameter and 3 or 6 mm long, respectively) were introduced in order to investigate the resulting improvement of the spalling behavior via a decrease of the pore pressure due to vaporization of water. Two slabs at a time were subjected to pre-specified temperature histories, i.e., the ISO fire curve (prEN1991 1-2 2002) or the HCI (hydrocarbon fire with $T_{max} = 1300°$C). Figure 1 shows the experimental setup. In order to cover the bright and reflective oven walls, steel plates were placed in areas visible on the movie sequences. During the fire experiments, the temperature history was recorded in the oven and at selected depths from the heated surface. Spalling was recorded visually by (i) a video camera, producing real-time movies, and (ii) a high-speed camera recording selected spalling events at a rate of 250 frames per second.

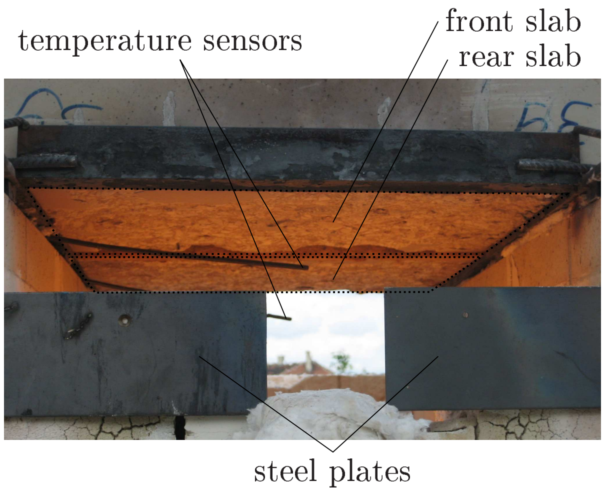

Figure 1. Experimental setup used within spalling experiments.

Since spalling (especially explosive spalling) is a very quick process, only the slow-motion sequences could be used to investigate the size/shape and to compute the velocity of the concrete pieces that got detached from the heated surface. The intensity of certain spalling events could be assessed from the acoustics of the event and the from time sequences before and after certain spalling events, accessible via the real-time movies.

Within the experiments, all previously mentioned types of spalling were observed. Whereas the most violent type of spalling (explosive spalling) was observed mostly as surface spalling, corner spalling was rather slow (i.e., progressive spalling with low velocity). Moreover, the size of some pieces originating from corner spalling was considerably bigger than the size of all pieces from surface spalling. The size (and, hence, the mass) was found to be inversely-proportional to the velocity of distinct pieces, with smaller velocities for bigger pieces. Aggregate spalling was observed to be of explosive as well as progressive type. In some events, no distinct spalled-off pieces could be identified but a cloud of chips was visible.

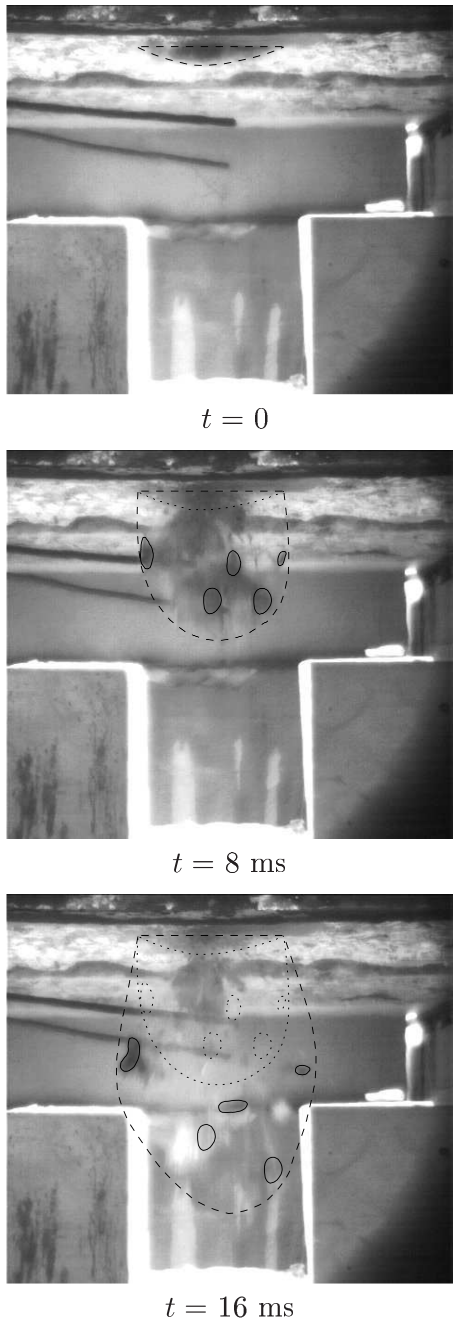

Figure 2. High-speed camera images from spalling experiments (C60/75): position of spalling front for three time instants.

Figure 2 shows three screen shots of a selected spalling event (surface spalling). The dashed lines mark the location of the spalling front at selected time instants, whereas the solid lines mark distinct spalled-off pieces. It can be seen that the spalling front (i.e., the fastest small-sized chips) moves faster than the distinct spalling pieces and also that the pieces move with different velocities. For the depicted

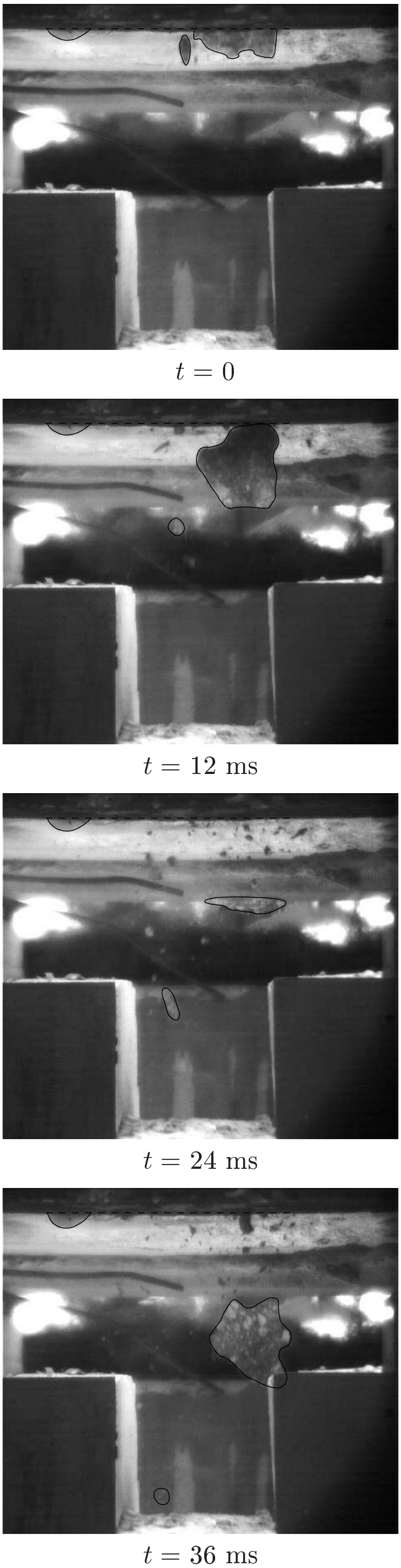

Figure 3. High-speed camera images from spalling experiments (C30/37): concrete pieces with different size and velocity.

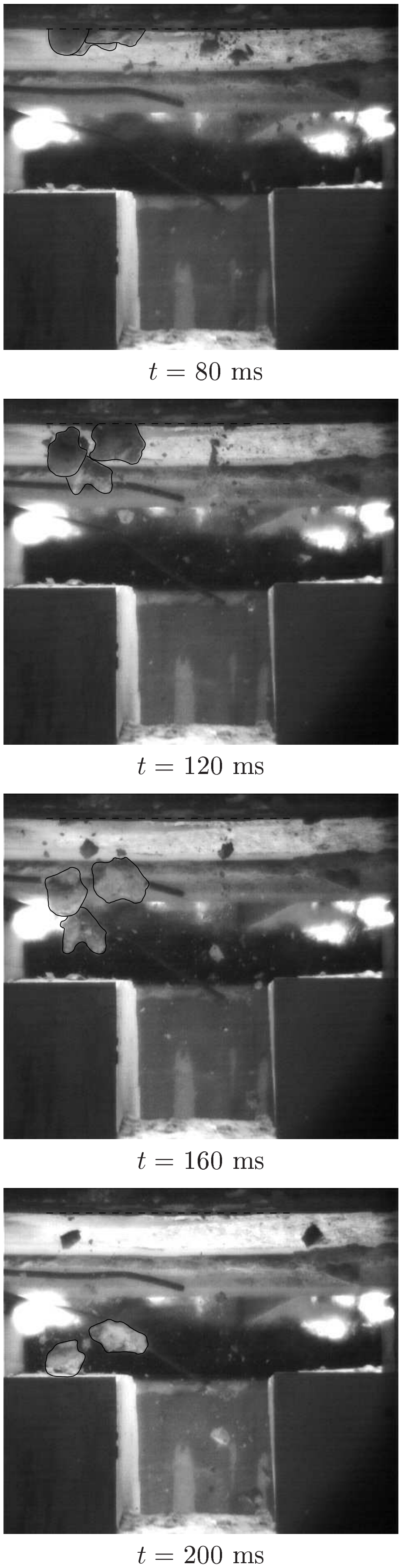

Figure 4. High-speed camera images from spalling experiments (C30/37): concrete pieces in free fall, no further acceleration.

spalling event, the velocity of the spalling front was calculated as $v_{front} = 12$ m/s, whereas the velocity of the five distinct pieces lied within the range of $5.6 \leq v_{piece} \leq 12$ m/s.

Figures 3 and 4 show a spalling event that can be defined as corner spalling since the pieces originate from the front edge of the specimen. In Figure 3, the big plate-like piece is apparently much slower than the small piece, with velocities being 2.8 and 6 m/s, respectively. The marked concrete pieces in Figure 4 move with an even lower velocity. Calculations showed that the velocity of the marked pieces may be explained exclusively by gravity acceleration[1], meaning the pieces were simply detached from the specimen and fell downwards after that.

Figure 5 shows the distribution of the velocity of the spalling front observed during selected spalling events recorded with the high-speed camera. The results indicate the existence of two peaks: one within the range of $7.5 \leq v_{front} \leq 9$ m/s and a second not so distinct peak within the range of $13.5 \leq v_{front} \leq 15$ m/s. In Figure 6, the minimum and maximum velocities of distinct spalled-off pieces are displayed for every recorded spalling event. In case only one piece was visible within the spalling event, minimum and maximum velocities are equal. Pieces with a velocity $v_{piece} \leq 1.5$ m/s were considered as being accelerated only by gravity forces, denoted as free-fall pieces. From the identified minimum and maximum velocity of distinct spalled-off pieces determined for every spalling event, the distribution of v_{piece}^{min} and v_{piece}^{max} is depicted in Figure 7. As previously indicated, Figures 5 and 7 show that the velocity of the spalling front (Fig. 5) is greater than that of single pieces (Fig. 7). The distribution of the minimum of v_{piece} indicates again the existence of two peaks, in this case lying within the range of $3 \leq v_{piece}^{min} \leq 4.5$ m/s and $6 \leq v_{piece}^{min} \leq 7.5$ m/s, respectively. As in case of v_{front}, the second peak is smaller. The maximum of v_{piece}, on the other hand, exhibits one peak, lying within the range of $6 \leq v_{piece}^{max} \leq 7.5$ m/s.

[1]Figure 4 shows three pieces in free fall. The length of the path these pieces are visible in the slow-motion sequence is $L = 13$ cm. Starting at the bottom surface of the specimen with zero velocity, the time span for a piece to move a distance $L = 13$ cm is given by

$$t = \sqrt{\frac{2L}{g}} = \sqrt{\frac{2 \cdot 0.13}{9.81}} = 0.16 \text{ s}, \qquad (1)$$

with $g = 9.81$ m/s^2 as the gravity acceleration. The time span between the first and the last screen shot in Figure 4 is 0.12 s which – considering that the pieces are already in the downward motion in the first screen shot in Figure 4 – corresponds well to the situation of free fall.

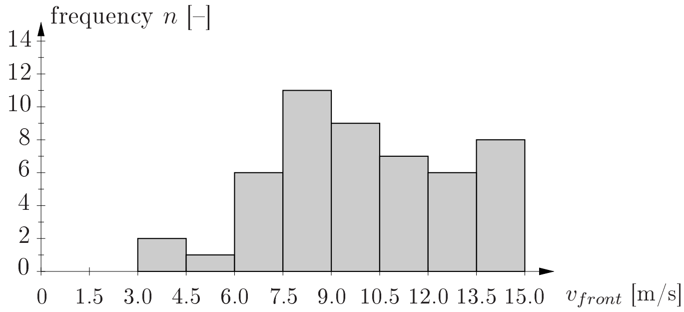

Figure 5. Distribution of velocity of spalling front recorded within fire experiments.

3 DISCUSSION

The origin of spalling is still open to debate (see, e.g., (Meyer-Ottens 1972; Anderberg 1997; Bažant 1997; Consolazio et al. 1997; Ulm et al. 1999; Kalifa et al. 2000; Schneider and Horvath 2002; Hertz 2003; Khoury and Majorana 2003; Khoury 2006)). As already indicated in Section 1, two phenomena are considered to cause spalling, namely thermo-hydral processes and thermo-mechanical processes.

When investigating the governing processes involved in concrete spalling, the released energy during a spalling event is considered (Gawin et al. 2006). Hereby, the kinetic energy of the spalled-off concrete piece is calculated. In case of thermo-mechanical processes, this kinetic energy is equal to the difference between the elastic strain energy stored in the piece prior to spalling and the fracture energy consumed during its dislocation. In case of thermo-hydral processes, this kinetic energy can be set equal to the performed work associated with the expansion of water vapor when the concrete piece is dislodged.

Numerical studies (Gawin et al. 2006) have shown that both the released elastic energy and the performed work during vapor expansion can result in a velocity in the range of $4 \leq v_{piece} \leq 5$ m/s. When a combination of the two described processes is considered, the resulting velocity becomes 7 m/s. In (Gawin et al. 2006), both thermo-mechanical and thermo-hydral processes are considered to influence the stress state within the concrete member, whereas the former (thermo-mechanical processes) are considered to initiate cracking and, hence, spalling. The latter (thermo-hydral processes) are not considered to cause spalling without the former, i.e., the assistance of stresses in consequence of restrained thermal dilation, which are present in every concrete structure subjected to heating. Thermo-hydral processes, however, are considered to substantially contribute to the acceleration of the spalled-off piece, depending on the magnitude of the gas pressure within the concrete structure. In (Gawin et al. 2006), the ratio between kinetic energies resulting from thermo-mechanical and thermo-hydral processes lies within the range of 1:1 to 1:6.

According to (Bažant 2005), thermo-hydral pro-

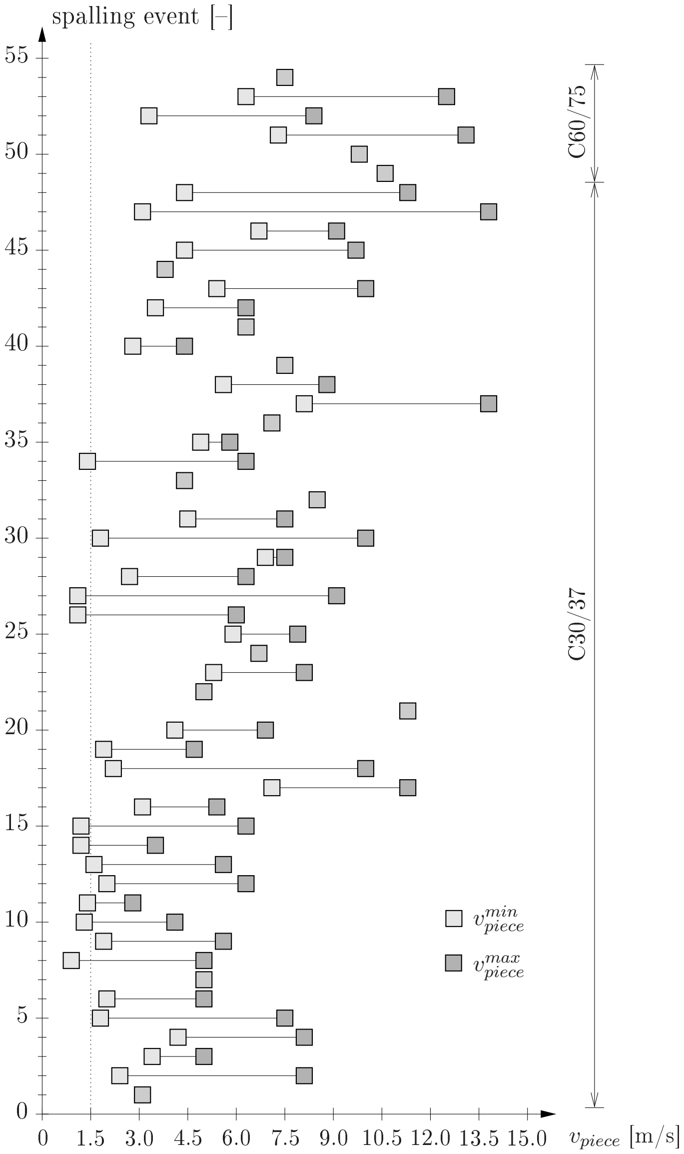

Figure 6. Minimum and maximum velocity of distinct spalling pieces determined for every recorded spalling event.

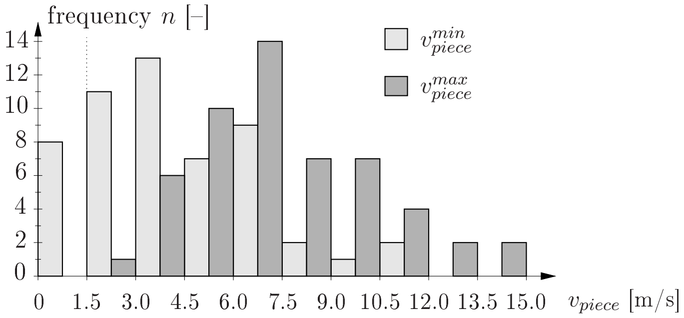

Figure 7. Distribution of minimum and maximum velocity of distinct spalling pieces within recorded spalling events.

cesses are not the major source for explosive spalling. They, nevertheless, contribute to the triggering of fracture and crack opening. Furthermore, after cracking and during the crack opening, the pore pressure in the crack drops to zero almost instantly since the available volume increases by several orders of magnitude. Therefore, thermo-mechanical processes are considered as the major source for explosive spalling.

It is agreed upon the fact that in case of heating of concrete during fire loading, a combination of thermo-mechanical and thermo-hydral processes causes spalling (see, e.g., (Bažant 2005; Gawin et al. 2006; Khoury 2006)). Whether the former or the latter is the main driving process has not been clarified yet. In any case, the relative influence of these two processes depends on numerous factors, such as concrete strength, moisture content, heating rate, etc.

For the underlying spalling experiments, the contribution of the two described processes to the total amount of kinetic energy available for accelerating the spalled-off piece was investigated following the scheme outlined in (Gawin et al. 2006). As mentioned in (Gawin et al. 2006), the proposed quantitative analysis has only a simplified character and represents a rough estimate for the kinetic energy due to the fact that several assumptions are made (e.g., adiabatic vapor expansion, geometry of fracture and spalled piece) and some physical phenomena are neglected. Nevertheless, a trend could be extracted from investigating the selected spalling events depicted in Figures 2 to 4 in Section 2: the results indicate that the importance of thermo-mechanical and thermo-hydral processes depends on the water/cement-ratio and, hence, the concrete strength. In case of concrete with w/c = 0.35 (C60/75, see selected spalling event depicted in Figure 2), the ratio between kinetic energies associated with thermo-mechanical and thermo-hydral processes turned out to be approximately 1:1. In case of concrete with w/c = 0.55 (C30/37, see selected spalling event in Figure 3), on the other hand, thermo-hydral processes had a higher influence with the ratio being approximately 1:4. The velocities determined from the so-obtained kinetic energy and the corresponding mass of the spalled-off piece were found in the range of the measured velocities reported in Section 2.

4 CONCLUSIONS

Spalling of near-surface concrete layers considerably influences the stability of concrete structures subjected to fire loading. Two types of processes are considered to be mainly responsible for spalling: (i) thermo-mechanical and (ii) thermo-hydral processes. Within recently conducted fire experiments, spalling was recorded visually, giving insight into the size/shape and velocity of spalled-off pieces, allowing assessment of the released kinematic energy during acceleration of the concrete pieces.

Within the fire experiments, different types of spalling were observed ranging from (i) explosive spalling with velocities of up to 14 m/s and (ii) progressive spalling with smaller velocities to (iii) fall-off of concrete pieces with the gravity as the only source of acceleration.

Both thermo-mechanical and thermo-hydral processes are considered to contribute to spalling, the relative importance of the two processes has not been clarified yet and is subject of discussion. Within the underlying spalling experiments, the resulting kinetic energy from these two processes was estimated using the simplified analysis scheme proposed in (Gawin et al. 2006). The results indicated that the ratio between the kinetic energies originating from thermo-mechanical and thermo-hydral processes, respectively, is dependent on the *w/c*-ratio and, hence, the concrete strength. In case of concrete with a lower *w/c*-ratio (resulting in a higher concrete strength), thermo-mechanical and thermo-hydral processes were equally important, whereas thermo-hydral processes contributed to a larger amount to the total kinetic energy in case of concrete with a higher *w/c*-ratio.

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