Loadbearing capacity criteria in fire resistance testing

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ABSTRACT

The European system for fire testing and classification of loadbearing building elements lacks consistency because the two standards that have to be applied prescribe different criteria for assessing the loadbearing performance. This article analyzes the implications of the present conflict between the standard for testing and the standard for classification. The prescribed criteria for loadbearing performance are related to the exceedance of deflection and rate of deflection thresholds. A database of 46 fire resistance tests performed at the University of Liege is collected that contains the time at which these thresholds are reached in fire tests with different typologies of elements (walls, floors, columns and beams). Then, the loadbearing performance (and hence the fire resistance rating) can be derived according to the two standards. The evolutions of deflection and rate of deflection during the tests are also analyzed to gain a better understanding of the adequacy of the standards. The selection of one or the other standard affects the time at which "failure" is deemed to occur in fire tests. Statistically speaking, the difference in terms of failure time that results from using one or the other standard has a 25% probability to exceed 10%. In certain cases, this results in a difference in fire resistance rating; this was observed for 3 of the analyzed tests. The apparent contradiction in two codes in application has potential practical implications and therefore needs to be solved. The article suggests some guidelines for defining homogenized and consistent criteria.

Keywords: *Fire Resistance; Laboratory Testing; Loadbearing Capacity Criteria; Deflection Rate*

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1. Introduction

1.1 Background

Experimental testing may be used to assess the fire resistance of building elements. For comparing the results of tests made in different laboratories on various types of elements, the tests have to be performed under well-defined standardized conditions. The established standards define the heating and loading conditions, but also the performance criteria that have to be applied to measure the fire resistance duration.

In Europe, the procedure that leads to the classification of building elements with regards to fire resistance involves a two level process. In the first stage, one or several tests are performed by a laboratory that must have accreditation according to ISO 17025. Each test leads to the issue of a **test report**. In the second stage, a competent body compiles the test report and issues a **classification report**, the results of which can then be used by the different stakeholders of the construction process, e.g. by authorities having jurisdiction.

An important performance criteria that can be applied and results in a classification is related to the loadbearing capacity. This performance has to be assessed for building elements with a loadbearing function. Yet, it appears that the test standard (CEN 2012) and the classification standard (CEN 2009) (which are both currently in application) prescribe different criteria for assessing the loadbearing performance. More specifically, these two standards consider different logical combinations of the criteria used to define loss of loadbearing capacity. This leads to an inextricable situation which has to be fixed in order to lead to a consistent and credible system for testing and classification of building elements in fire.

The fire resistance lab of University of Liege has been conducting, for many years, experimental tests on loadbearing building elements that cover the main typologies of building elements. These data are used in this paper to investigate the consequences of adopting one or the other of the loadbearing definitions currently given in the standards.

1.2 Standard definitions of the loadbearing capacity performance

The loadbearing capacity is defined as the time in completed minutes for which a test specimen continues to maintain its ability to support the test load during the test (CEN 2012). Obviously, this definition calls for a second definition relative to the ability to support the test load. Support of the test load should be assessed objectively and based on criteria that reveal imminent failure. Indeed, it is not desirable to pursue experimental tests until complete failure of the test specimen, because this could damage the testing facilities and raise safety issues for the personnel.

This study focuses on two European standard codes, the fire resistance test standard (CEN 2012) and the classification standard (CEN 2009). It is important to compare these two standards because they are both used in the two level process followed in Europe for classification of loadbearing building elements with regards to fire resistance. Hence, discrepancies or contradictions between these two standards raise an important issue.

The two standard codes base their criteria on the amount of deflection (in mm) measured during the test and rate of deflection (in mm/min) calculated from these measurements. Limiting thresholds are set for the deflection and rate of deflection of construction elements. These thresholds depend on the typology of the element (CEN 2012). For flexural loaded elements, they are given by Eqs (1) and (2).

$$D = \frac{L^2}{400\,d} \quad \text{Eq. 1}$$

$$\frac{dD}{dt} = \frac{L^2}{9000\,d} \quad \text{Eq. 2}$$

where D is the limiting deflection (in mm), L is the clear span of the test specimen (in mm), d is the distance from the extreme fiber of the cold design compression zone to the extreme fiber of the cold design tension zone of the structural section (in mm), and dD/dt is the limiting rate of deflection (in mm/min).

For vertically loaded elements, the limiting values (thresholds) are given by Eqs (3) - (4).

$$C = \frac{h}{100} \quad \text{Eq. 3}$$

$$\frac{dC}{dt} = \frac{3h}{1000} \quad \text{Eq. 4}$$

where C is the limiting vertical contraction (i.e. negative elongation, in mm), h is the initial height (in mm) of the test specimen, and dC/dt is the limiting rate of vertical contraction (in mm/min). Given that a contraction is an axial deflection, the same word “deflection” will be used in this paper to refer equally to “deflection of flexural loaded elements” and “vertical contraction of vertically loaded elements”.

These criteria on the deflection and rate of deflection are accompanied by two comments in the test standard (CEN 2012). First, since relatively rapid deflections can occur until stable conditions are reached, the rate of deflection criteria is not applied in the first 10 min of the fire test. Second, the deflection value has to be set to zero at the commencement of the fire test. This means that zero point for deflection is measured after applying the load and before commencement of heating. This latter requirement from the general test method standard is also present in the test method standards for specific typologies of elements, e.g. for beams (CEN 1999-a) or for columns (CEN 1999-b).

Thus, the criteria of Eq. 1-4 allow for determining the ability of an element to support the test load. However, the two considered standards differ in their interpretation of the logical combination of the criteria that indicates failure. According to fire resistance test standard (CEN 2012), failure to support the load is deemed to have occurred when **one of the two criteria** has been exceeded, i.e. whether the deflection or the rate of deflection. Hence, the loadbearing capacity is lost when the first of both criteria (“deflection” or “rate of deflection”) is met. On the other hand, the classification standard (CEN 2009) states that the loadbearing capacity is lost when **both criteria** are met. In other words, the classification standard considers the latest of the two criteria met as the one determining the loadbearing capacity, whereas the test standard considers the earliest one.

There is thus a discrepancy between the definitions of loadbearing capacity performance given by the test standard and by the classification standard. Both standards use the same definitions for the limiting criteria (thresholds) but differ in their logical combination of these criteria. This automatically results in different definitions for the loadbearing capacity performance when the thresholds for the deflection and for the rate of deflection are not met simultaneously. At the time being, no clear solution to this discrepancy is offered and this leads to endless discussions between the sponsors of the tests, the laboratories performing the tests, the body doing the classification and the authorities.

Finally, it has to be noted that the test standard has evolved from its first version in 1999 to the current version (2012). In its first version, the test standard adopted the definition based on the exceedance of both criteria (deflection threshold *and* rate of deflection threshold). It also stated that the rate of deflection criteria shall not be applied until a deflection of L/30 is exceeded. The first version of the classification standard was issued in 2003; it adopted the same definition (*"both criteria"*) but without any limitation on the application of the rate of deflection criteria. An updated version of the classification standard was issued in 2009 without any modification on the loadbearing capacity definition; this is the version currently in application. Both test and classification standards thus used to be consistent regarding the main definition of loadbearing capacity. Then in the version of the test standard issued in 2012, the definition was modified and based on the exceedance of "*one of the two criteria*". The limitation on the rate of deflection criteria was also modified and now refers to "*the first 10 min of the fire test*". However, the classification standard was not revised accordingly. The modifications in the 2012 version of the test standard thus resulted in the current situation of conflict between the definitions of the loadbearing capacity.

1.3 Objectives of the research

Given this conflict between test and classification standards, the question arises as to which definition is most relevant and what are the consequences of using one or the other.

In this document, the results of 46 fire resistance tests on loadbearing elements performed in the Fire Testing Laboratory of the University of Liege (Belgium) between 2005 and 2014 are collected. The tested elements cover the main typologies of building elements, namely walls, floors, beams and columns. The "deflection" and "rate of deflection" criteria are processed for each test. The objective is to provide a database for analyzing the fire response of loadbearing elements with regards to the standards that are in application nowadays. This means that the results of the tests performed before 2012 have been re-evaluated according to the current version of the test standard (CEN 2012). Then, analyses are conducted on these data with the aim to highlight the implications of the present conflict between standards. Finally, conclusions are drawn in order to provide useful information and recommendations to the attention of the scientific community involved with fire resistance testing, as well as to the authorities in charge of resolving the conflict between both standards.

2. Test Data

Table 1 summarizes the main data from the 46 tests considered for the analysis.

Test nr	Test element	Test standard	End of test [min]	Deflection criterion time [min]	Rate of deflection criterion time [min]
1062	Wall (Masonry-)	EN 1365-1	167.4	NA	167.4
1065	Wall (Masonry-)	EN 1365-1	136.9	NA	NA
1066	Wall (Masonry-)	EN 1365-1	29.5	29.5	29.3
1070	Wall (Masonry-)	EN 1365-1	35.2	NA	NA
1081	Wall (Masonry-)	EN 1365-1	148.4	NA	NA
1083	Wall (Masonry-)	EN 1365-1	302.9	NA	NA
1084	Wall (Masonry-)	EN 1365-1	256.6	NA	NA
1102	Floor/Roof (Other-)	EN 1365-2	59.8	NA	58.5
1120	Column (Steel-conc. composite-)	EN 1365-4	88.8	88.6	87.2
1121	Column (Steel-conc. composite-)	EN 1365-4	22.2	NA	22.0
1122	Column (Steel-conc. composite-)	EN 1365-4	64.3	NA	64.3
1123	Column (Steel-conc. composite-)	EN 1365-4	42.5	NA	42.4
1117	Floor/Roof (Timber-)	EN 1365-2	70.2	NA	NA
1124	Column (Steel-conc. composite-)	EN 1365-4	56.5	NA	56.5
1125	Column (Steel-conc. composite-)	EN 1365-4	64.2	NA	NA
1126	Column (Steel-conc. composite-)	EN 1365-4	38.7	NA	38.7
1127	Column (Steel-conc. composite-)	EN 1365-4	78.9	NA	78.9
1128	Column (Steel-conc. composite-)	EN 1365-4	103.3	NA	NA
1129	Column (Steel-conc. composite-)	EN 1365-4	35.0	NA	NA
1140	Beam (Steel-conc. composite-)	EN 1365-3	53.9	50.9	47.8
1141	Beam (Steel-conc. composite-)	EN 1365-3	78.1	70.6	73.2
1142	Beam (Steel-conc. composite-)	EN 1365-3	67.4	63.1	66.0
1143	Beam (Steel-conc. composite-)	EN 1365-3	165.4	142.5	165.3
1144	Beam (Steel-conc. composite-)	EN 1365-3	44.5	41.9	37.2
1145	Beam (Steel-conc. composite-)	EN 1365-3	85.5	83.3	79.3
1146	Beam (Steel-conc. composite-)	EN 1365-3	95.6	75.2	88.1
1147	Beam (Steel-conc. composite-)	EN 1365-3	93.6	NA	93.2
1148	Wall (Timber-)	EN 1365-1	139.7	NA	NA
1205	Floor/Roof (Other-)	EN 1365-2	37.6	37.3	37.2
1167	Floor/Roof (Timber-)	EN 1365-2	63.8	NA	NA
1180	Column (Steel-)	EN 1365-4	22.2	NA	21.6
1181	Column (Steel-)	EN 1365-4	19.7	NA	NA
1182	Column (Steel-)	EN 1365-4	20.5	NA	20.2
1212	Wall (Timber-)	EN 1365-1	120.1	NA	NA
1213	Wall (Timber-)	EN 1365-1	61.3	NA	NA
1183	Column (Steel-conc. composite-)	EN 1365-4	108.4	NA	NA
1229	Beam (Steel-conc. composite-)	EN 1365-3	120.0	NA	NA
1231	Beam (Steel-conc. composite-)	EN 1365-3	102.7	NA	NA
1224	Column (Steel-)	EN 1365-4	12.1	NA	11.8
1223	Column (Steel-)	EN 1365-4	11.9	11.8	11.3
1225	Column (Steel-)	EN 1365-4	11.8	11.8	11.2
1233	Wall (Masonry-)	EN 1365-1	120.2	NA	NA
1280	Beam (Steel-)	EN 1365-3	18.7	18.4	14.8
1296	Floor/Roof (Other-)	EN 1365-2	30.0	25.5	15.4
000G	Beam (Steel-)	EN 1365-3	28.7	28.5	24.3
000H	Beam (Steel-)	EN 1365-3	28.9	28.7	24.5

NA Criterion not achieved at the end of the test

Table 1 Test database with raw results.

The flexural loaded elements (i.e. beams and floors/roofs) are tested in a 4 m long furnace. They are subjected to uniform loading or point loading. The vertically loaded elements (i.e. columns and walls) are tested in a 3.25 m high furnace. These elements are subjected to concentric or eccentric axial loading.

The load is applied by the use of weights for uniform loading and by hydraulic actuators otherwise and is maintained constant during the fire test. In all cases, the loading conditions comply with the test standards requirements.

Regarding the support conditions, special devices are used to avoid friction in the hinges and in free horizontal supports. Fig. 1 shows a hinge connection used for a column test (left) and a rolling hinge support used for a beam test (right).

Fig. 1 Hinge connection used for a column test (left) and rolling hinge support used for a beam test (right)

In Table 1, "NA" stands for "not achieved" meaning that the test was stopped before the criterion was met. The reason why the test was stopped is either because the fire resistance time targeted by the sponsor of the test was reached, or because security reasons (relative to the integrity of the equipment or to safety of personnel) has incited the manager of the lab to stop the fire test.

For the data analysis presented in the following, this notation is adopted: f is the deflection; f_L is the limiting deflection (criterion); $f_n = f / f_L$ is the normalized deflection; $f' = df / dt$ is the rate of deflection; f'_L is the limiting rate of deflection (criterion); $f'_n = f' / f'_L$ is the normalized rate of deflection; Δt is the time increment between two measurements (sampling period).

During the tests, the deflection is measured at a typical average acquisition sampling period of 3 to 4 seconds.

The rate of deflection is processed from the deflection measurements by numerical differentiation. The differentiation is performed with a finite difference method by centered differences (non-causal) to avoid a phase delay phenomenon (i.e. time shift). Its scheme is chosen to be a second order error, according to: $f'_i = \frac{f_{i+1} - f_{i-1}}{2\Delta t} + \mathcal{O}(\Delta t^2)$. Note that for the first and the last samples, the scheme is logically reduced to a forward difference and a backward difference of first order error.

The rate of deflection values are then passed through a moving average filter (low-pass filter). The aim is to provide a smoothed signal by reducing the high frequency noise of mechanical and numerical origin. This filter is performed with a rectangular filter kernel whose length is chosen as 120 sec in the time domain. In some cases, the length of the kernel has to be reduced in the vicinity of failure because of the very sharp slope of the signal at this time, depicting a strong acceleration or deceleration of the deflection. Reduction of the kernel length is done in these areas until the filtered signal fits properly the original one. This helps to maintain a sharp filtered response and consequently to determine the failure time accurately. More information about this numerical processing of the signal can be found in (Dumont 2015).

For each considered test in Table 1, the limiting deflection and limiting rate of deflection are calculated using Eq. 1-2 or Eq. 3-4, depending on the element typology. Then, the times at which the criteria are met can be obtained and are reported in Table 1.

Finally, “normalized deflections” and “normalized rates of deflection” are also processed by dividing deflection values and rate of deflection values by their limiting (i.e. threshold) values. These normalized quantities are not shown in Table 1 but they are used in the subsequent sections of the paper for drawing all the test data on a same nondimensional chart.

3. Evolution of Deflection and Rate of Deflection during the Fire Tests

3.1 Method

The aim of this section is to gain an insight into the behavior exhibited by building elements during the fire tests in terms of evolution of the deflection and rate of deflection. The database of Table 1 is used for the analysis.

For each test, time is eliminated from the evolution of the normalized deflection and normalized rate of deflection to produce a parametric curve that can be plotted in the space (f_n ; f'_n). The normalized deflection f_n is plotted on the horizontal axis whereas the normalized rate of deflection f'_n is plotted on the vertical axis. The behavior of a building element during a fire test is represented by a curve in this normalized space. In addition, the limiting criteria (thresholds) in terms of deflection and rate of deflection can be represented as vertical and horizontal lines, respectively; by definition these lines cross the horizontal and vertical axes at a value of 1.

The definitions of the loadbearing capacity performance can be illustrated in the normalized space. According to the test standard (CEN 2012), failure to support the load occurs when one of the criteria is met, i.e. when the curve representing the tested element response crosses the continuous red lines in Fig. 2a. These continuous lines represent the border of the space in which the element is deemed able to support the test load. In contrast, the classification standard (CEN 2009) states that failure occurs when both criteria are met, which corresponds to a very different setting of the "border" continuous lines as shown in Fig. 2b.

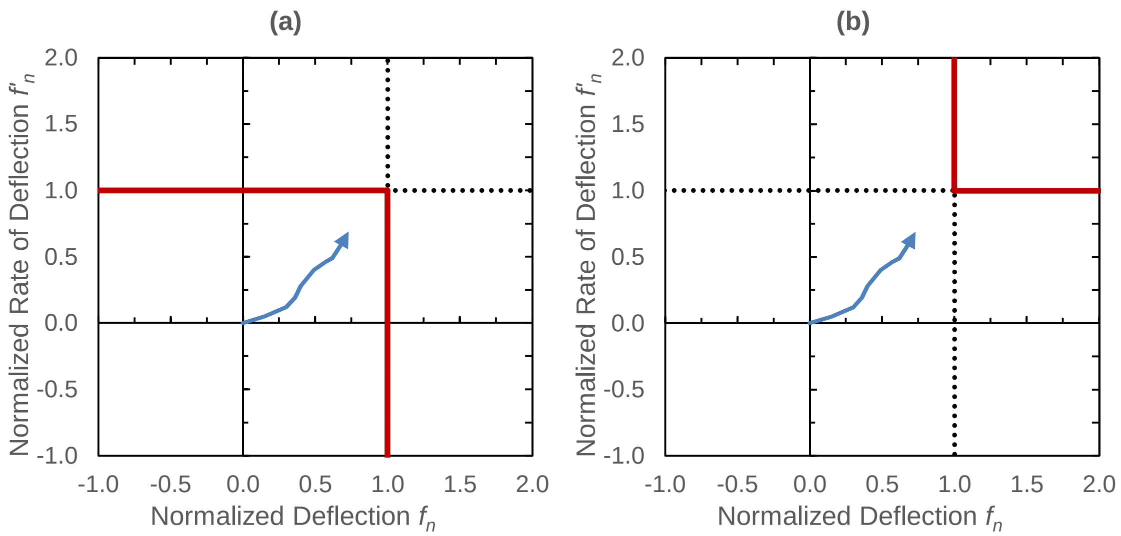

Fig. 2 Border of the loadbearing capacity criteria according to the test standard (a) and the classification standard (b)

It is interesting to highlight the following properties of the curves representing the element response in the normalized space:

(1) Since the deflection value is set to zero at the commencement of the fire test, the curves start from the origin of the system of coordinates.

(2) For vertically loaded elements, the normalized deflection is positive for contraction. Due to thermal expansion, the curves related to these elements are expected to start towards negative normalized deflection and negative normalized rate of deflection at the beginning of the fire test.

(3) For flexural loaded elements, the normalized deflection is positive for a downward displacement. The curves related to these elements are expected to remain in the space of positive normalized deflection and positive normalized rate of deflection during the entire fire test duration.

(4) As the rate of deflection is the derivative of the deflection, a curve can only progress towards higher normalized deflections ("towards the right") when in the positive normalized rate of deflection area (upper half space). Inversely, a curve can only progress towards lower normalized deflections ("towards the left") when in the negative normalized rate of deflection area (lower half space).

3.2 Vertically loaded elements

3.2.1 Columns

The dataset comprises 6 steel columns and 11 composite steel-concrete columns. All columns are heated symmetrically on four sides. The response of the columns is plotted in the normalized space in Fig. 3. Note that Fig. 3b shows the same results as Fig. 3a but the horizontal and the vertical axes are stretched in Fig. 3b to show the complete curves for the steel columns.

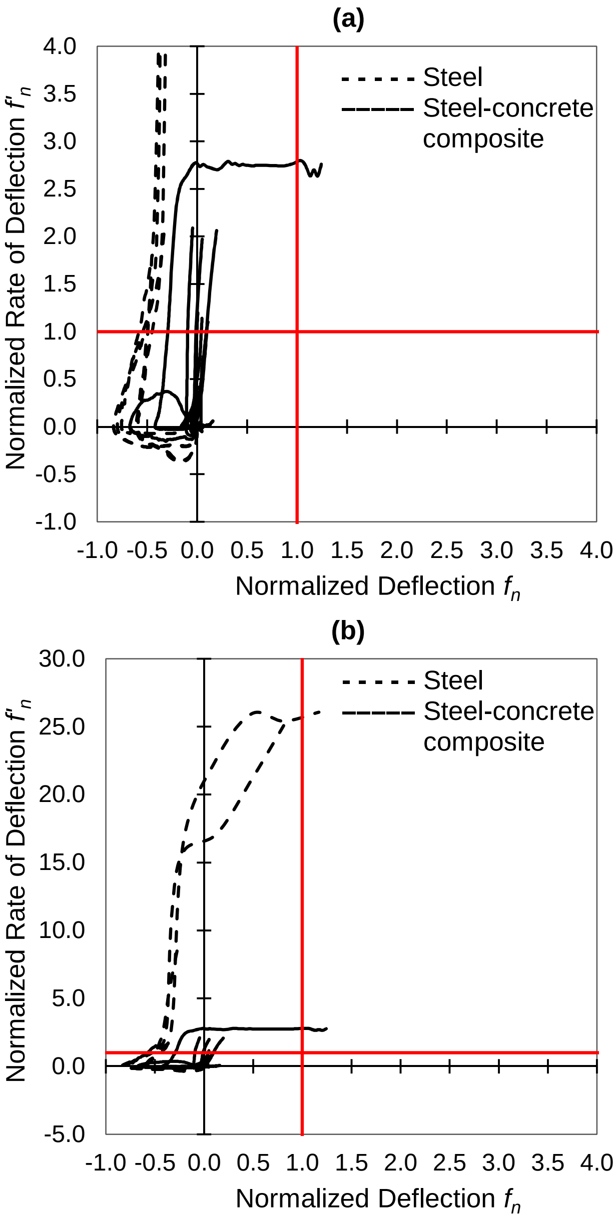

Fig. 3 Evolution of the normalized deflection and rate of deflection for columns. Results are shown for 6 steel columns and 11 composite steel-concrete columns. The same data is plotted on (a) and (b) with a different y-axis scale. The plots for several of the columns lie on top of each other

As can be seen from Fig. 3a, the criterion relative to the rate of deflection is always met prior to the criterion relative to the deflection. When the test was pursued until reaching the deflection criterion, the latter was met at a high deflection rate (f'_n greater than 2.5 and even up to 25 for steel columns with small sections).

In fact, the limiting deflection defined for vertically loaded elements (Eq. 3) represents a very significant level of contraction. This level is not always achieved during fire testing because of security reasons that incite to stop the fire test. As an illustration, Fig. 4 shows the deflected shape of a column at a normalized deflection of $f_n = 1.5$. For this column, the limiting deflection (contraction) is 25 mm and the contraction reached is 37 mm.

Fig. 4 Deflected shape at the end of a fire test after exceedance of the deflection criterion

3.2.2 Walls

The dataset comprises 8 masonry walls and 3 timber walls. The term "timber wall" refers to walls made from a timber studs structure. The response in the normalized space is plotted in Fig. 5. Note that Fig. 5b shows the same results as Fig. 5a but with different axis scales to focus on the plots for timber walls. Vertical lines indicate a sudden collapse of the wall during the fire test.

Masonry walls are very likely to meet the rate of deflection criterion first, because of a sudden collapse, as shown by Fig. 5. For such fragile elements, the limiting deflection criterion corresponds to a very significant contraction, which is not very realistic. Fire tests are rarely pursued until such contraction levels are reached because it would endanger the testing equipment. As an illustration, Fig. 6 shows the deflected shape of a masonry wall at the end of a fire test while the normalized deflection was equal to $f_n = -0.06$. Out of plane displacements are visible and indicate failure, despite the fact that the deflection is far from reaching the defined threshold. In fact, the wall was still experiencing an elongation and not yet a contraction, as indicated by the negative value of the normalized deflection.

Regarding the timber walls, the 3 tests were stopped before any of the criteria were met. The deflections and rates of deflection remained very limited. Also, no negative value of the deflection is observed since timber walls do not give rise to thermal expansion.

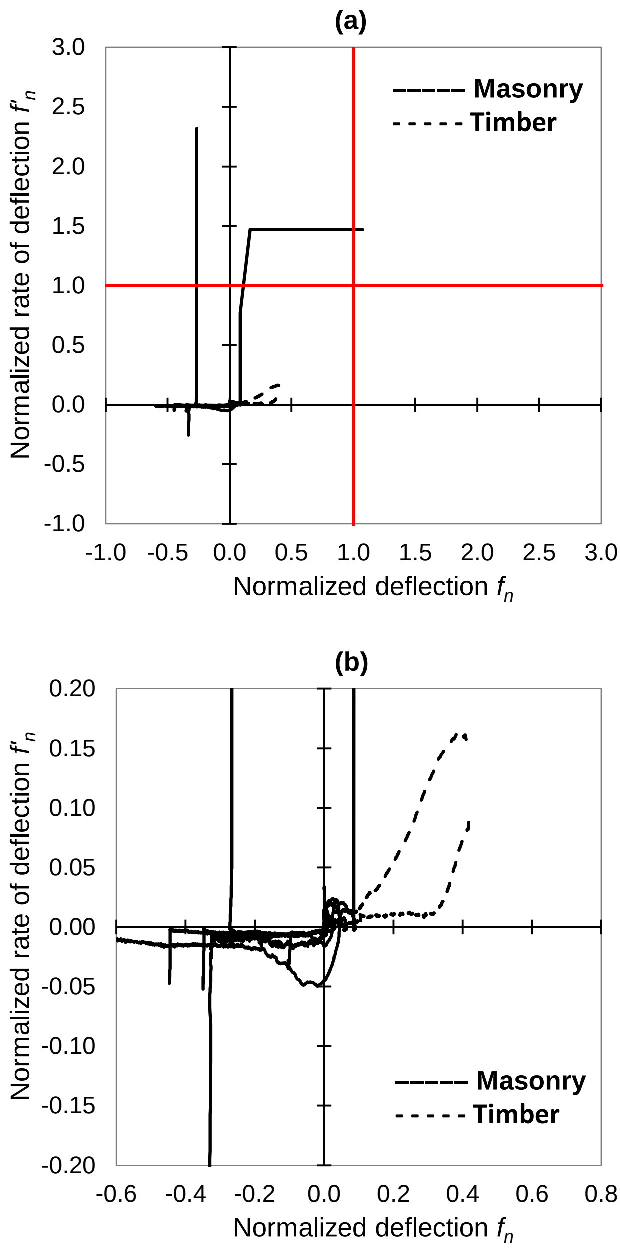

Fig. 5 Evolution of the normalized deflection and rate of deflection for walls. Results are shown for 8 masonry walls and 3 timber walls. The same data is plotted on (a) and (b) with different axis scales. The plots for two of the timber walls lie on top of each other

Fig. 6 Deflected shape of a masonry wall at the end of the fire test

3.3 Flexural loaded elements

3.3.1 Beams

The dataset comprises 10 concrete beams and 3 steel beams. The responses of the beams are presented on Fig. 7. Fig. 7b shows the same results as Fig. 7a with the horizontal and the vertical axes stretched to show the complete curves for the steel beams.

For the steel beams, the first criterion that is met during the fire test is the rate of deflection in all three cases. For these beams, when the deflection criterion is finally met the normalized deflection rate f'_n exceeds 9 (Fig. 7b).

The concrete beams consist in either reinforced concrete beams or composite steel-concrete beams. Fig. 8 shows the cross-section of two of the test specimens, one composite beam and one reinforced concrete beam.

For the concrete beams, the first criterion that is met is the deflection criterion in some cases and the rate of deflection criterion in other cases (Fig. 7a). Actually, concrete beams are the only elements out of the 46 tests considered in this study for which, in some cases, the deflection criterion was met prior to the deflection rate criterion. This occurred for 4 of them, all of which were composite.

3.3.2 Floors and Roofs

The tested floors and roofs consist of one steel inner structure floor, one solid wood floor, one timber structure floor, one metal sandwich panel roof (mineral insulated core) and one steel deck polyisocyanurate (PIR) insulated roof. The response for all floors and roofs are presented on Fig. 9a while Fig. 9b focusses on the timber floors.

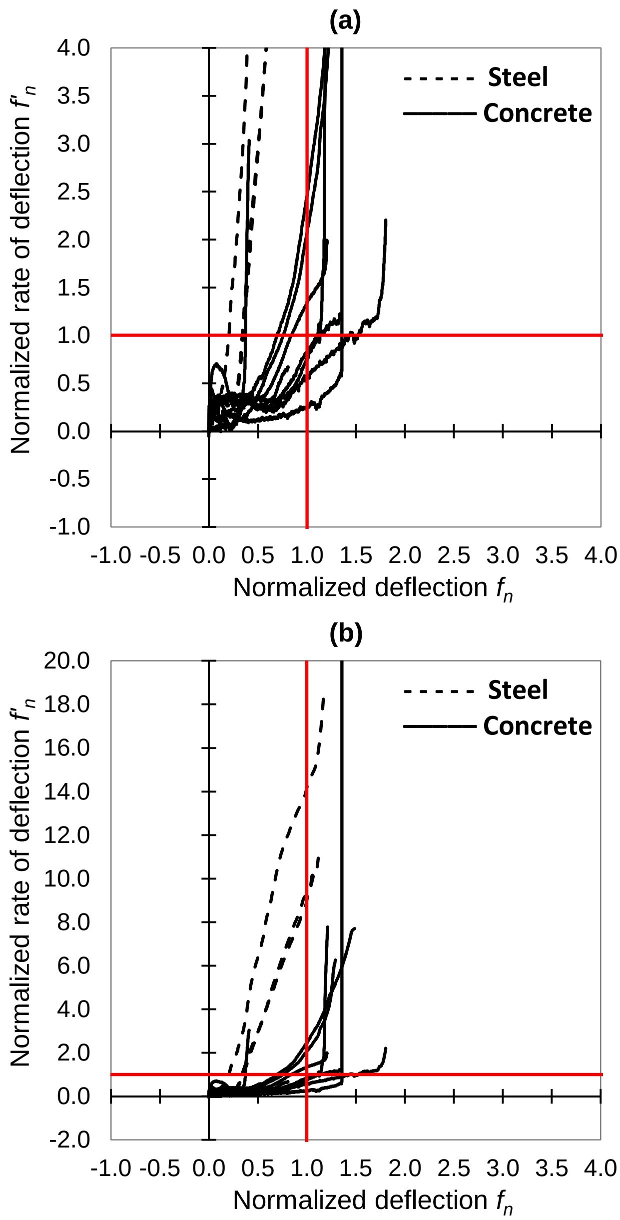

Fig. 7 Evolution of the normalized deflection and rate of deflection for beams. Results are shown for 10 concrete beams and 3 steel beams. The same data is plotted on (a) and (b) with a different y-axis scale

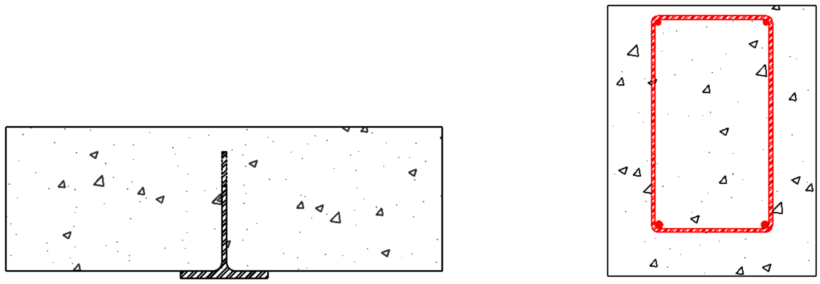

Fig. 8 Examples of sections of composite and reinforced beams

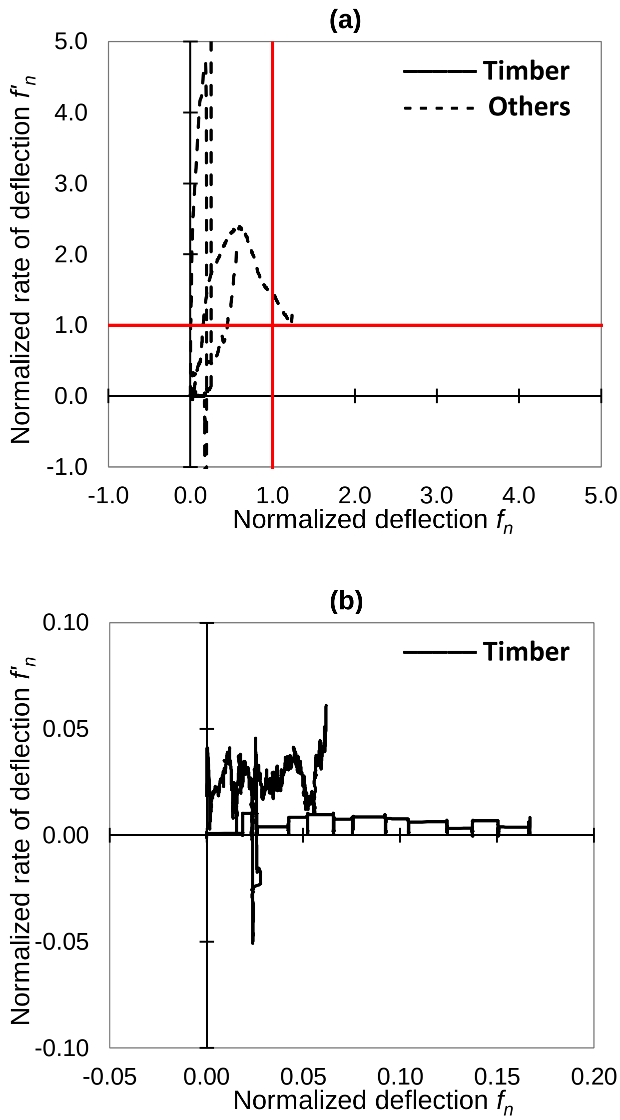

Fig. 9 Evolution of the normalized deflection and rate of deflection for (a) all the tested floors and roofs and (b) for the timber floors only. Note the change of axis scales

In this figure, a vertical line indicates a sudden failure of the tested element. This occurred for the metal sandwich panel roof. Regarding the tested timber floors (Fig. 9b), the two tests were stopped before any criterion was met. Timber floors are characterized by very low values of deflection and rate of deflection. This is due to the fact that timber as a material does not experience significant thermal expansion, so timber floors do not exhibit any thermal bowing. Besides, timber has a stress-strain relationship that is approximately linear elastic up to failure, with no distinct plastic elongation. These assumptions on the behavior of timber at elevated temperature are the ones considered in Eurocode 5 (CEN 2004).

For the other elements for which the test could be pursued until a criterion was met, the first criterion was always the rate of deflection. Metal sandwich panel roof (mineral insulated core) is the only considered element (out of the 46 tests) for which the rate of deflection exceeded the limiting value in the first 10 min of the fire test. According to the standard code

(CEN 2012), this part of the curve has to be discarded. This roof finally collapsed after 38 min, see Fig. 10.

Fig. 10 Metal sandwich panel roof with mineral insulated core

4. Time of Failure according to the Different Standards

Based on the evolution of the normalized deflection and rate of deflection, the loadbearing capacity performance (or, equivalent, the time of failure) of the tested elements can be determined. As discussed in Section 1.2, selection of the test standard or the classification standard will lead to different definitions for the loadbearing capacity, see also Fig. 2 for a graphical interpretation. The objective of this section is to determine the loadbearing capacity according to the two standards for all tests of the database and analyze the differences and resulting implications.

4.1 Method

For most of the tested elements in the database, the fire tests were not conducted until exceedance of the two criteria, either because of sudden failure of the element or because of security considerations with regards to the testing equipment in the laboratory. Specifically, the following situations are encountered:

(i) 16 tests were carried out beyond the limiting threshold of both the deflection criterion and the rate of deflection criterion.

(ii) 12 tests were carried out beyond the threshold of the rate of deflection criterion, but stopped before the threshold of the deflection criterion.

(iii) 18 tests stopped before the threshold of any criterion.

(iv) for none of the test was the deflection criterion met while the rate deflection criterion was not met.

In order to compare the implications of using one or the other standard for definition of the failure time, it is necessary to have a database of tests for which the times corresponding to the two criteria are known. As is, the current database comprises only 16 tests for which the two criteria were met. However, it is possible to include the 12 tests of the situation (ii) into this database, provided an extrapolation is performed. The extrapolation method is described in three steps.

- Step 1: The analyses conducted in Section 3 show that the rate of deflection is very unlikely to decrease once the rate of deflection threshold has been exceeded. This can be observed for instance in Fig. 3 and Fig. 7. In fact, a decrease in the rate of deflection when the element is beyond a normalized deflection rate of 1 but below a normalized deflection of 1 has only been observed for one test (Fig. 9a). This was probably due to the particularity of the tested roof, made of a steel deck with PIR insulation. As a result, it seems reasonable to assume that, for a test that was stopped prematurely, the deflection rate beyond the end time of the test would have been greater or equal than its value at the end time of the test. This assumption is expressed by the following equation:

$$f'(t \succ t_{end}) \geq f'_{end} \quad \text{Eq. 5}$$

Between the lower limit ($f' = f'_{end}$) and upper limit ($f' \rightarrow \infty$), a linear extrapolation of the deflection speed in the time domain is assumed as a reasonable estimation, see the following equation:

$$f'(t \succ t_{end}) = f''_{end}.(t - t_{end}) + f'_{end} \quad \text{Eq. 6}$$

For the considered tests, the rate of deflection is positive (since the threshold has been exceeded) and remains positive (given the considerations here above). Hence, the deflection can only increase. In other words, the expected curve representing the element response beyond the end time of the test inevitably moves towards the limiting value of the deflection criterion, see Fig. 11.

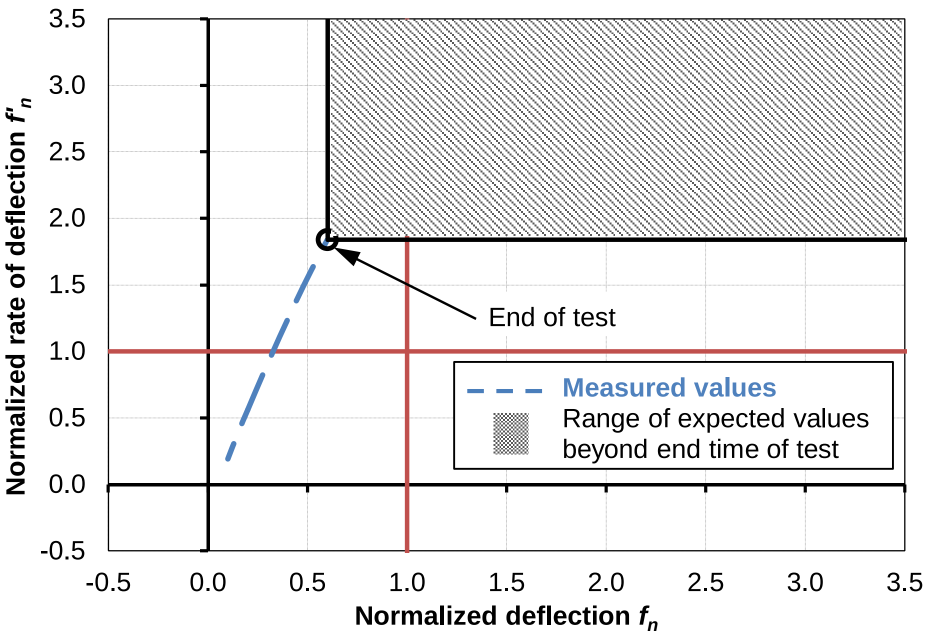

Fig. 11 Domain of expected values beyond end time of the test in the normalized space

- Step 2: an estimation of the expected behavior of the deflection beyond the end time of the test can be predicted using Eq. 7. The expected deflection is calculated from the linear extrapolation model of Eq. (6), and the extreme values are processed from the lower limit ($f' = f'_{end}$) and upper limit ($f' \to \infty$) of the deflection rate.

$$f = \int_0^t f'\,dt = f_{end} + \int_{t_{end}}^t f'\,dt \qquad \text{Eq. 7}$$

- Step 3: Finally, the reversed equation predicts the expected failure time of the deflection criterion, noted t_{fL}, and its limit values. The lower limit time is the one achieved when the deflection rate keeps a constant value equal to the one at the end of the test; the upper limit time is the one achieved when the deflection rate is assumed to be infinite; the expected time is the one achieved when the rate of deflection continues to rise linearly.

This data enhancement processing is performed on the 12 tests of the second configuration. It allows predicting the extrapolated time at which the deflection criterion is met for these 12 tests, as well as the lower and upper limits for this time. These times are reported in Table 2. Note that the difference between the lower limit and the upper limit of the enhanced values is rather limited, which gives some credibility to the extrapolated values. In the end, Table 2 includes the data for the 16 tests that were conducted until exceedance of both criteria plus the 12 tests for which the time of exceedance of the rate of deflection was experimentally obtained and the time of exceedance of the deflection is extrapolated.

Test nr	Test element	End of test [min]	Deflection criterion time [min]			Rate of deflection criterion time [min]
			Lower limit	Criterion time	Upper limit	
1062	Wall (Masonry-)	167.4	167.4*	167.9*	169.2*	167.4
1066	Wall (Masonry-)	29.5		29.5		29.3
1102	Floor/Roof (Other-)	59.8	59.8*	61.9*	64.6*	58.5
1120	Column (Steel-conc. composite-)	88.8		88.5		87.2
1121	Column (Steel-conc. composite-)	22.2	22.2*	22.9*	23.5*	22.0
1122	Column (Steel-conc. composite-)	64.3	64.3*	65.2*	67.1*	64.3
1123	Column (Steel-conc. composite-)	42.5	42.5*	43.2*	44.1*	42.4
1124	Column (Steel-conc. composite-)	56.6	56.6*	57.9*	59.3*	56.5
1126	Column (Steel-conc. composite-)	38.8	38.8*	39.6*	41.5*	38.7
1127	Column (Steel-conc. composite-)	79.0	79.0*	79.6*	80.6*	78.9
1140	Beam (Steel-conc. composite-)	54.0		50.9		47.8
1141	Beam (Steel-conc. composite-)	78.1		70.6		73.2
1142	Beam (Steel-conc. composite-)	67.4		63.1		66.0
1143	Beam (Steel-conc. composite-)	165.4		142.5		165.3
1144	Beam (Steel-conc. composite-)	44.5		41.9		37.2
1145	Beam (Steel-conc. composite-)	85.5		83.3		79.3
1146	Beam (Steel-conc. composite-)	95.6		75.2		88.1
1147	Beam (Steel-conc. composite-)	93.6	93.6*	95.6*	98.0*	93.2
1205	Floor/Roof (Other-)	37.6		37.3		37.2
1180	Column (Steel-)	22.2	22.2*	23.1*	24.3*	21.6
1182	Column (Steel-)	20.5	20.5*	21.9*	23.2*	20.2
1224	Column (Steel-)	12.1	12.1*	12.3*	12.6*	11.8
1223	Column (Steel-)	11.9		11.8		11.3
1225	Column (Steel-)	11.8		11.7		11.2
1280	Beam (Steel-)	18.7		18.4		14.8
1296	Floor/Roof (Other-)	30.0		25.5		15.4
000G	Beam (Steel-)	28.7		28.5		24.3
000H	Beam (Steel-)	28.9		28.7		24.5

*** extrapolated value**

Table 2 Test data base used for the failure time analysis

4.2 Analysis

The analysis of the loadbearing capacity performance (i.e. failure time) according to the two standards is conducted based on the data in Table 2. This table contains the time at which the deflection and rate of deflection criteria are met for the 28 tests. Regarding the deflection criterion, the expected value of the criterion time is used in the cases where an extrapolation was conducted.

The test standard states that the loadbearing capacity is reached as soon as one criterion or the other is met, i.e. the earliest of the two times. On the other hand, the classification standard requires both criteria to be met, i.e. the loadbearing capacity is the latest of the two criterion times reported in Table 2. For a given test, the selection of one or the other standard leads consequently to a different failure time. This is illustrated in Fig. 12 where, for each test, the time of failure is reported on the vertical axis according to the test standard and the classification standard.

The following observations can be made from Fig. 12:

- By definition, the failure time given by the classification standard is always higher or equal than the one given by the test standard.
- The difference in loadbearing capacity is higher than 3 minutes in 10 out of 28 tests and higher than 5 minutes in 3 out of 28 tests.
- The difference reaches up to 23 minutes in one test performed on a composite beam (test 1143) and, interestingly, both deflection and rate of deflection criteria were actually reached during the test (meaning that there is no extrapolation in the value of 23 min).
- For 3 out of the 28 considered tests, the (loadbearing capacity) rating is affected by the choice of the standard. For instance, the test 1102 fails after 58 minutes or 61 minutes depending on which standard is selected. Hence, its fire resistance rating could change from R45 to R60. Similar conclusions are drawn for the tests 1280 and 1296 that can achieve R15 and R20 respectively or not depending on the applied standard.

The relative difference (in %) is computed between the failure time according to the test standard and the classification standard (with the test standard as the reference value). The average value of the relative differences for the sample shown in Fig. 12 is found equal to 8.7% and the standard deviation to 13.0%.

The cumulative frequency of the relative difference in failure time is plotted in Fig. 13. The obtained frequency can be fitted by a lognormal distribution. The lognormal distribution with parameters μ=1.44 and σ=1.28 (mean and standard deviation of the natural logarithm of the relative difference) gives a good prediction for the relative difference in failure time (in %). This lognormal distribution is suggested as a representative model of the relative difference distribution.

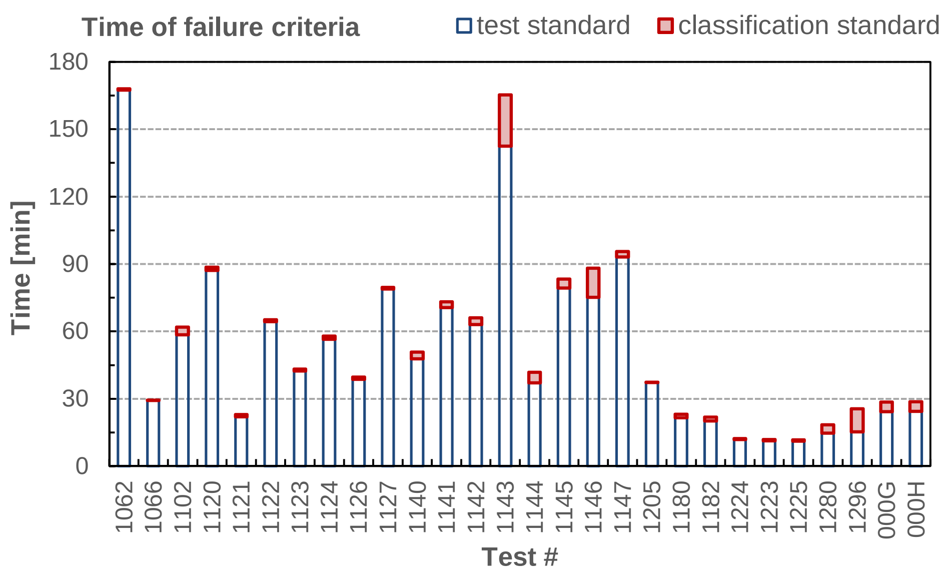

Fig. 12 Time of failure according to the test standard and the classification standard

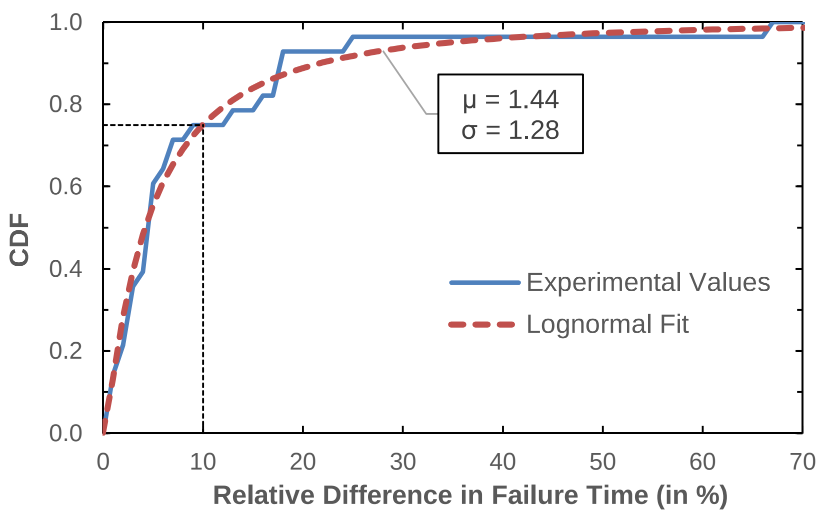

Fig. 13 Cumulative frequency of the relative difference in failure time between the two standards

The curve in Fig. 13 should be interpreted as follows. When performing a loadbearing test on a specimen, the relative time difference between the attainment of the first of the criteria (either deflection or rate of deflection) and the attainment of the second of them, is expected to be lower than the value on the x-axis with a probability given on the y-axis. For example, the difference is expected to be lower than 10% with a probability of 75%.

5. Discussion

The current discrepancy in the test and classification standards is an issue, as shown in the previous sections. It is not satisfactory from a scientific point of view. In addition, it can lead to a different fire rating for a loadbearing component depending on the standard definition that is adopted. This section discusses the current propositions and additional considerations related to this issue.

5.1 Proposals discussed in TC 127 WG1

In order to solve the conflict between test and classification standards, an alternative definition of the loadbearing capacity performance has been considered within Working Group 1 of the CEN Technical Committee 127. This new definition relies on three statements as given hereafter:

(i) The loadbearing capacity is attained at a time at which the first of both "deflection" or "rate of deflection" criteria is met.

(ii) The rate of deflection criterion is not applied in the first 10 min of the fire test.

(iii) The rate of deflection criterion is not applied until the deflection criterion has achieved half of its limiting value.

Compared with the current definition adopted in the test standard (see Section 1.2), this proposal differs with the latter only by the third statement. For the 28 tests of Table 2, it appears that this proposal does not lead to a significant modification of the failure time, as compared with the previous test standard definition. The difference is lower than 1 minute in 23 out of 28 tests. The maximum value of the difference is 4 minutes. Hence, the difference turns out to be limited. As a result, this proposal does not really allow for a better convergence between the test and classification standards.

Another proposal is based on common practice used when testing elements or substructures which are deemed to have a brittle failure mode. Such elements are typically characterized by the fact that the deformations are very small until failure. For such elements, the person in charge of the test decides to remove the load and stop the test based on his experience and, certainly, as soon as the result expected by the sponsor has been reached. This procedure has many shortcomings. What is the experience of the lab? What is the expected result in a scientific research program? A human factor is introduced which increases the level of uncertainty and decreases the repeatability. Yet, there is little alternative when the displacements are so small that no deflection or rate of deflection can be used.

Based on this observation, it has been proposed to adopt a similar definition of failure for all types of structural elements. Why would indeed ductile elements be penalized by deflection criteria that are not / cannot be applied to brittle elements? The fire resistance time with respect to load bearing capacity is then either the time of real physical collapse (still to be defined, for example when the load cannot be maintained) or the time when the test was stopped if the load was still supported at that time. The shortcomings mentioned here above remain.

5.2 Influence of the test data processing

Establishing a clear definition of the failure criteria is a necessary step for the standardization of testing and classification processes. In addition, it should also be ensured that different laboratories use identical methods to obtain and process the data.

For fire resistance testing of loadbearing components, the deflections are directly measured during the test. To the authors' knowledge, all the accredited European fire testing laboratories carry out the test deflection measurements with dedicated sensors (i.e. position transducers designed for the direct, absolute measurement of displacement). Then, the rates of deflection are computed as time derivatives of the deflection measurements. This can be done using different numerical methods and the choice of the method has an influence on the result. In particular, three aspects are examined hereafter, namely (i) the acquisition sampling period during the test, (ii) the numerical differentiation method for the calculation of the rate of deflection, and (iii) the numerical low-pass filtering of the calculated rate of deflection.

(i) Regarding the acquisition sampling period, the following requirement is mentioned in EN 1363-1: "*In the case of loadbearing test specimens, measurements shall be made prior to and following the application of the test load and at 1 minute intervals during the heating period*". This requirement should not be understood as restricting the acquisition sampling period at 1 minute. As a consequence to the imprecise character of this requirement, different labs may and certainly do use different sampling periods. Shorter periods should be preferred, when technically feasible, for the sake of accuracy.

(ii) Given the measured values of deflection, the rate of deflection must be obtained by numerical differentiation. The choice of the numerical differentiation method affects the result (i.e. the calculated rate of deflection).

The backward difference scheme makes use of present and past measures, and is therefore a causal differentiation method. This method results in a time delay in the calculated derivative, as compared with the mathematically exact value of this derivative. The backward delay effect occurs as soon as the signal is no longer linear, which is generally the case when dealing with real signals. The order of magnitude of the delay is half the differentiation step.

In contrast, the centered difference scheme makes use of additional future measures, and is therefore a non-causal differentiation method. This is a second-order method which does not produce any (significant) time shift.

The method to use for calculating the rate of deflection is not specified in the standard. It has been observed (EGOLF 2015) that different laboratories use different numerical differentiation methods and therefore, based on the same deflection measurements, provide different (i.e. shifted) values for the rate of deflection. Since the rate of deflection takes part in the definition of the loadbearing capacity, this may result in a difference in fire resistance. However, application of the code requirement related to the 1 minute sampling period ensures that this difference remains limited to about 0.5 minute. The fact that the difference is directly proportional to the sampling period explains why a short sampling period results in a short time shift in case of a backward difference method.

(iii) The numerical differentiation of the deflection measures produces a signal for the rate of deflection. This signal must be filtered to reduce the noise, which can be of mechanical and numerical origin.

The moving average is the most common low-pass filter, mainly because it is the easiest filter to understand and use. In spite of its simplicity, the moving average filter is optimal for a common task: reducing random noise while retaining a sharp step response. As the name implies, the moving average filter operates by averaging a number n of points from a raw signal to produce each point in the filtered signal. This filter can be used in a backward, a forward or a centered scheme. Use of one or the other of these schemes to the obtained rate of deflection curve results in a different time shift between the filtered and the raw signal.

In the case of fire testing, the deflection measurements are typically acquired at a sampling period shorter than one minute, e.g. 10 seconds. Yet, in order to derive the rate of deflection from the deflection measurements, a backward difference scheme with a step of 60 seconds is typically used. These numerically derived values are thus passed through a backward moving average filter which leads to a systematic delay of 30 seconds in the evaluation of the rate of deflection. This delay should be taken into account when assessing the failure time based on the rate of deflection. More information can be found in (Dumont 2015).

5.3 Load performance criteria in other standards

It is interesting to compare the European situation with the American (ASTM 2014) and British (BSI 1987) test standards concerning their definition of the load bearing capacity.

The American and British test standards provide no predefined criterion for most elements. The British standard states that, for loadbearing vertical elements, "*failure of the test construction shall be deemed to have occurred when the specimen fails to support the test loading*", and recognizes in its annex that "*it has not been possible to define the point at which specimens of vertical elements are deemed to be incapable of supporting the test loading*".

Similarly, the American test standard states that, for loadbearing walls, columns, floors, roofs and restrained beams, "*the test is successful if the test specimen sustains the applied load during the fire-resistance test for a period equal to that for which classification is desired*".

Only for some horizontal elements, the two standards give predefined criteria to assess the time at which failure is deemed to have occurred. The British test standard states that, for loadbearing horizontal elements, the loadbearing capacity is exceeded when **one of the two** following criteria is exceeded:

$$D = L/20 \qquad \text{Eq. 8}$$

$$\frac{dD}{dt} = \frac{L^2}{9000\,d} \qquad \text{Eq. 9}$$

However, the threshold on the rate of deflection (Eq. 9) shall not be applied until a deflection of L/30 has been exceeded.

This limit on the rate of deflection criterion is to be compared with the limits set by the European test standard ("*shall not be applied in the first 10 min of the fire test*") and in the proposal discussed in TC 127 WG1 (“*shall not be applied until the deflection criterion has achieved half of its limiting value*”). For the test data of the present study, it appears that, in the very large majority of cases, half of the deflection limiting value represents a value smaller than L/30. Hence, the former is reached earlier in the test than the latter. Therefore, the limit set by the British test standard is more restrictive than the one discussed in TC 127 WG1.

On the other hand, the American test standard gives predefined criteria only for loaded unrestrained beams supporting floors and roofs. For these elements, the loadbearing capacity is exceeded when **both of the two** following conditions are exceeded:

$$D = \frac{L^2}{400\,d} \qquad \text{Eq. 10}$$

$$\frac{dD}{dt} = \frac{L^2}{9000\,d} \qquad \text{Eq. 11}$$

There is no condition on the application of the rate of deflection threshold. The criteria defined in the American test standard are thus similar to the criteria of the European classification standard (CEN 2009) for this specific type of elements.

6. Conclusion and Recommendations

This paper has presented a critical analysis of the results of 46 fire resistance tests performed in the Fire Testing Laboratory of the University of Liege. The analysis focuses on the definition of the loadbearing capacity criteria. More specifically, it investigated the effect of the adopted standard codes on the definition of the failure time for the test sample.

Two standard codes that are currently in application provide different definitions for the time at which the loadbearing capacity is exceeded in a structural component tested in the fire situation. Both codes base their definition on the amount and rate of deflection. However, one of the codes (test standard) requires only one of these metrics to exceed a threshold for defining the failure, whereas the other code (classification standard) considers that failure occurs when the two metrics exceed their respective threshold.

The paper reviewed the evolution of the amount and rate of deflection for the 46 tests. Then, it highlighted the differences in terms of failure time that result from using one or the other standard code. For the analyzed data, the difference in failure time was higher than 3 minutes for 10 of the tests and it reached up to 23 minutes in one case. The choice of one or the other standard affects the fire resistance rating for 3 of the tests. These results demonstrate that the issue (i.e. the apparent contradiction in two codes in application) is not anecdotic but has potential practical implications and therefore needs to be solved.

Based on the work, the authors recommend considering the following guidelines:

1. The presented results show that the rate of deflection is the first criterion to be met on most cases, and that this criterion usually reflects the imminence of an instability.

2. For vertically loaded elements, the deflection threshold represents a very high level of contraction. Only very ductile test specimens (steel) are expected to reach this limit, whereas almost all others element are expected to collapse early in a brittle mode (masonries, timber structures, etc). In the latter cases, security reasons incite to stop the fire test before reaching the deflection threshold. In consequence, the loadbearing capacity definition from the test standard (i.e. one criteria or the other) would be much more appropriate than the definition from the classification standard (i.e. one criteria and the other). More fundamentally, this raises the question of the relevant nature of measured vertical deflections in vertically loaded elements. Vertical deflections are influenced by thermal expansion that has nothing to do with collapse. Would not the horizontal displacement at mid-level be more relevant as it is directly linked to buckling phenomenon?

3. For flexural loaded elements tested up to 6 m length, the limiting value for the deflection may exceed 300 mm. Such high displacements tests may turn out to be complicated to manage (for reasons related to the equipment). In fact, as soon as deflection levels exceed values in the order of 200 mm, control of a fire test in laboratory becomes challenging. Consequently, for flexural loaded elements, the same observation is made as for vertically loaded elements due to operational reasons. Namely, the loadbearing capacity definition from the test standard should be favored over the classification standard, because it allows stopping the test as soon as the rate of deflection threshold is reached.

4. While it is recognized that different materials have different behaviors, it would not be convenient to build different criteria definitions for each encountered group of material. Among other shortcomings, this would lead to new questions for innovative structures or materials that will appear in the future and for which a criterion would not have been foreseen. Therefore, it is recommended to keep a unique definition of the criteria and associated thresholds for use with all constituting materials.

5. The numerical method to be used for computing the rate of deflection from the deflection measures should also be defined in the standard. This would allow for a harmonization in the data processing and would help avoiding systematic errors. A centered finite difference scheme should be preferred over a backward scheme. The

differentiation step for this finite difference should also be standardized, as is the case in the British and American test standards which specify a step of 1 minute.

It would be interesting if other labs could in the future analyze their experimental results following a similar method. These additional data would enrich the discussion on loadbearing capacity criteria in fire resistance testing, especially if other labs can introduce additional typologies not considered here, e.g. timber columns.

References

ASTM (2014) E119-14, Standard Test Methods for Fire Tests of Building Construction and Materials, ASTM International

BSI (1987) BS 476:Part20, Fire tests on building materials and structures – Part 20: Method for determination of the fire resistance of elements of construction (general principles), British Standards Institution, London

CEN (2012) EN 1363-1, Fire resistance tests - Part 1: General Requirements. CEN, Brussels

CEN (2009) EN 13501-2:2007+A1:2009, Fire classification of construction products and building elements – Part 2: Classification using data from fire resistance tests, excluding ventilation services. CEN, Brussels

CEN (2004) EN 1995-1-2, Eurocode 5 – Design of timber structures – Part 1-2: General – Structural fire design. CEN, Brussels

CEN (1999-a) EN 1365-4, Fire resistance tests for loadbearing elements – Part 4: Beams. CEN, Brussels

CEN (1999-b) EN 1365-3, Fire resistance tests for loadbearing elements – Part 3: Columns. CEN, Brussels

Dumont F (2015) Analysis of some finite difference schemes for slightly noisy time dependent signals. Internal Report, Fire Testing Laboratory, University of Liege, http://hdl.handle.net/2268/179486

EGOLF round-robin nr. TC2 14-1 in fire resistance testing (2015), public summary report RR EN 1363-1 and EN 1365-3. http://www.egolf.org.uk/documents/round-robin.html