FIRE-RESISTANT STEEL AT ELEVATED TEMPERATURES

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ABSTRACT

Visible steel structures are interesting from architectural point of view. However, in case of fire it is in general necessary to protect the steel from elevated temperatures to provide sufficient fire resistance. This can be attributed to its high thermal conductivity leading to fast heating and hence rapid decline of elastic modulus and effective yield strength. For members with reasonable load-ratios, it is not possible to meet the requirements for fire resistance time of 30 minutes using carbon steel. This means that costly intumescent coating has to be applied. Nowadays, the advancement of metallurgy allows for producing fire-resistant steel with enhanced mechanical properties at elevated temperatures. Thus, it becomes a genuine alternative to traditional fire protection systems.

1. INTRODUCTION

There are different means to assure fire safety of steel constructions. Traditional fire protection systems, such as plasterboard, spray or intumescent coating, are proven and tested. Nevertheless they are linked with an additional working process and therefore extra costs. The latter are mainly labour costs, which are high in industrialized countries.

In contrast to this, fire-resistant steel comes with inherent fire protection achieved by modified alloy. Thus, the owner can save significant labour costs. More reasons can be cited in favour of fire-resistant steel. The steel structure remains visible and hence architecturally appealing. Fire-resistant steel allows for fast erection of buildings using standardized connections. Besides, usable space is increased as fire protection can be omitted. In the aftermath of the World Trade Center disaster further aspects as robustness of fire protection and its integrity were spotlighted. Whereas traditional fire protection can be removed and is prone to damage this is not the case for fire-resistant steel. Composite solutions are excluded from this consideration. Seeing these advantages the rare use of fire-resistant steel bewilders at first glance. On closer inspection the reasons become clear. Both normative regulations and material properties for fire-resistant steel are missing.

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Accurate prediction of the material properties of fire-resistant steel is crucial for determining the load-bearing capacity of fire-exposed structures. Moreover, the scope of application for fire-resistant steel is not clear, e.g. if it is suitable for members in bending as well as members endangered by global instability.

For these reasons research work on fire-resistant steel performed by VALLOUREC & MANNESMANN TUBES addressed the arising questions. Research included both numerical and experimental investigations. On behalf of VALLOUREC & MANNESMANN TUBES, scientific support was provided by Leibniz Universitaet Hannover.

The project aimed at the algebraic formulation of the stress-strain relationship of newly developed fire-resistant steel, which is referred to as VM-FIRE in the following. Moreover, reasonable fields of application for the new product should be identified. Answer to the latter is dominated by the relative load-bearing behaviour of carbon steel. Thus, carbon steel is included in the following considerations.

2. STRESS-STRAIN RELATIONSHIP OF FIRE-RESISTANT STEEL VM-FIRE

2.1 Tests

Small-scale tests were performed by the research institute Salzgitter Mannesmann Forschung on behalf of VALLOUREC & MANNESMANN TUBES to establish the mathematical formulation of the stress-strain relationship of fire-resistant steel at elevated temperatures. A test series of small-scale transient state tests at high temperatures was conducted. The test set-up can be seen in Figure 1. On this basis, it was possible to establish the mathematical formulation of the fire-resistant steel. The material model is based on the formulation used in [1].

2.2 Determination of yield strength

Two tests at ambient temperature were performed in order to determine the yield strength. It is obvious that VM-FIRE does not have distinct yield strength. According to [2] yield strength is defined as $R_{p0.2}$, which is the stress at 0.2% residual strain. Yield strength of $R_{p0.2}$ = 458 MPa was determined. As this strength is clearly above the required nominal elastic limit, VM-FIRE can be classified as S355. The latter is characterized by its yield strength of 355 MPa.

Fig. 1 - Test set-up for small-scale tests.

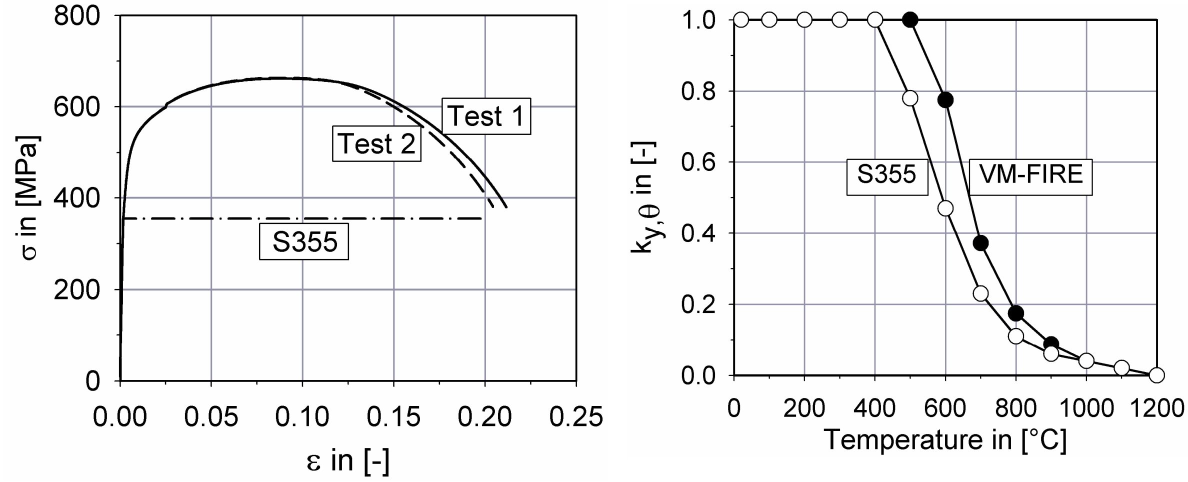

Fig. 2 - Results of tension tests at ambient temperature (left) and reduction factor $k_{y,\theta}$ of carbon and VM-FIRE steel for elevated temperatures (right).

On the left side of Figure 2, test results at room temperature are compared to the bilinear stress-strain curve of S355 steel according to [1]. Strains are noted nondimensionally, i.e. the proof limit $R_{p0.2}$ corresponds to $\varepsilon = 0.002$. Regarding Figure 2 it can be seen that the strength increase of VM-FIRE takes place for large strains. The elastic behaviour at small strains is very comparable to that of carbon steel. On the right side of Figure 2, improved strength retention can be noted for VM-FIRE at temperatures exceeding 400°C.

2.3 Transient state tests

Besides the tests at room temperature, transient state tests were performed by the research institute Salzgitter Mannesmann Forschung. It had been previously planned to perform tests at stress levels of 3, 10, 20, 40, 80, 120, 170, 355 and 466 MPa. Due to testing problems it was not possible to perform the tests with stresses less than 20 MPa. Test data is presented on the left side of Figure 3. Thermal strains were determined in a separate test with an unloaded specimen, which is not presented here.

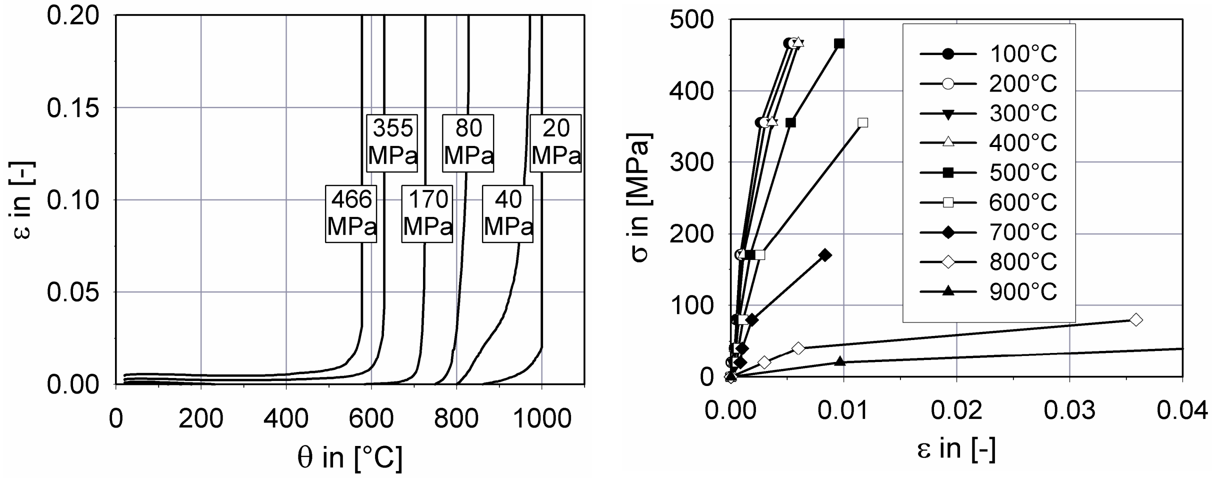

Fig. 3 - Results of transient state tests (left) and σ-ε-θ-curves for VM-FIRE steel (right).

Investigations aimed at the establishment of stress-strain formulae of VM-FIRE. Therefore the stress-strains curves for the different stress levels had to be cleared from thermal strains. These will be taken implicitly into account in the algebraic formulae.

3. EVALUATION OF SMALL-SCALE TESTS

Formulation of the newly developed fire-resistant steel VM-FIRE should lean to existing stress-strain relationships as defined for carbon steel in [1], which is based on [3]. The small-scale tests aimed at the identification of the different parameters defining this relationship, which are presented in Figure 8 in the Appendix. Detailed description of the mathematical formulation can be found in [1].

After reduction of the thermal strains it was possible to allocate mechanical strains to different stress levels. In accordance with [1] temperatures between 100°C and 900°C were considered with intermediate steps of 100°C. Higher temperatures could not be taken into account due to yielding of the specimens. The established σ-ε-θ-curves are shown on the right side of Figure 3.

This data was used to determine the necessary parameters describing the stress-strain relationship. Results of the latter are compared to test data in Figure 4 (left side). Each curve was established on the basis of six data points. Under these circumstances the agreement between experimental und numerical results can be regarded as acceptable. Additional tests would be required to amend the algebraic formulation in particular for small strains. However, it is not expected that this would result in major diversion in comparison to carbon steel.

3.1 Determination of the elastic range ($\varepsilon_{p,\theta}$, $f_{p,\theta}$ and $E_{a,\theta}$)

As a result of the limited number of test results, it was not possible to identify the elastic range. It would be necessary to perform further tests for stress levels less than 20 MPa in order to determine the transition from elastic to plastic behaviour. These tests could not be performed owing to immediate yielding of the steel.

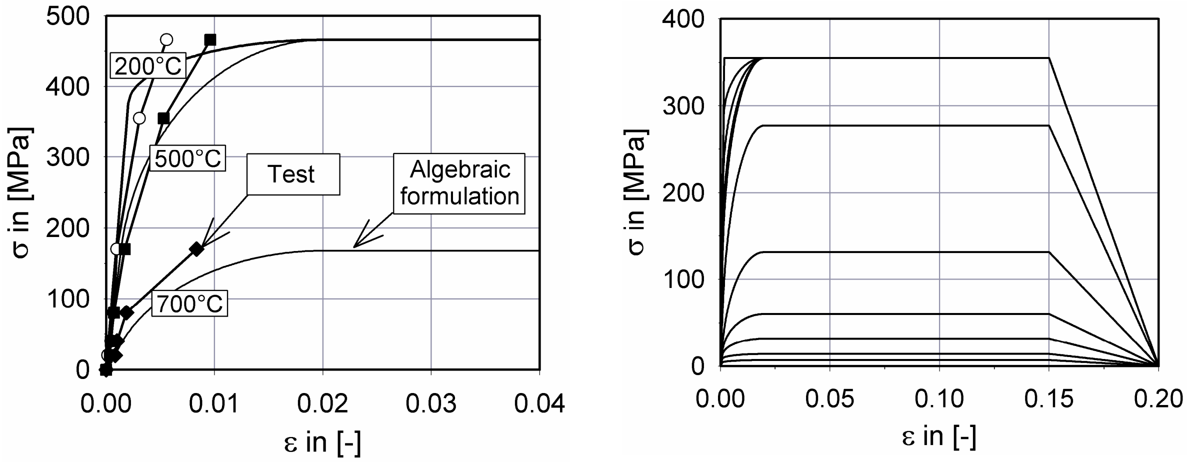

Fig. 4 - Comparison between test data and algebraic formulation of VM-FIRE steel for selected σ-ε-θ-curves (left); determination of σ-ε-θ-curves for VM-FIRE after transformation to nominal yield strength (right).

Thus, it was not possible to define all reduction factors for the fire-resistant steel VM-FIRE. As it is shown later-on, knowledge of these parameters is not compulsorily required. Therefore the corresponding parameters of carbon steel were taken for the VM-FIRE steel.

3.2 Determination of the yield point ($\varepsilon_{y,\theta}$ and $f_{y,\theta}$)

The effective yield strength $f_{y,\theta}$ could be identified on the basis of the carried out experimental work. Resulting values are shown on the left side of Figure 2. The yielding strain $\varepsilon_{y,\theta}$ was chosen as 0.02, which is in accordance with [1]. For temperatures exceeding 900°C, the corresponding values of carbon steel were assumed to be also valid for VM-FIRE steel as experimental data was not available.

3.3 Determination of the limiting strain for yield strength and ultimate strain ($\varepsilon_{t,\theta}$ and $\varepsilon_{u,\theta}$)

The transient state tests could not be performed until rupture of the test specimens. Therefore the according parameters of carbon steel were chosen for VM-FIRE steel. This results in a limiting strain for yield strength $\varepsilon_{t,\theta} = 0.15$ and ultimate strain $\varepsilon_{u,\theta} = 0.20$.

3.4 Transformation to nominal elastic limit

As previously shown, the actual yield strength of $R_{p0.2} = 458$ MPa was considerably higher than the nominal yield strength of 355 MPa. For a comparison between the stress-strain curves it was necessary to transform the actual to the nominal strength. The strains and stresses were hence transformed using the subsequent factor. Resulting stress-strain curves are shown on the right side of Figure 4.

$$\eta = \frac{f_{y,\mathrm{Nominal}}}{f_{y,\mathrm{Actual}}} = \frac{355\ \mathrm{MPa}}{458\ \mathrm{MPa}} = 0.775 \leq 1 \qquad (1)$$

With:

$f_{y,\mathrm{Nominal}}$	Nominal strength;
$f_{y,\mathrm{Actual}}$	Actual proof limit $R_{p0.2\%}$.

Knowledge of the material properties concerning the elastic range is crucial for the investigated columns that are prone to global instability. Because of the small number of stress levels it was not possible to establish all necessary parameters to describe the material model according to [1]. As it will be shown later-on, numerical validation of the established material model at test results showed nevertheless good agreement between computed and tested failure times of columns consisting out of VM-FIRE steel.

The reason for this is that there could not be expected significant divergence between the elastic modulus of VM-FIRE and carbon steel. Bleck and Muenstermann [4] investigated on the influence of different alloys on the elastic modulus. It is confirmed that modification of alloy has only minor influence. Therefore the elastic modulus of the newly developed fire-resistant steel VM-FIRE should approximately correspond to that of carbon steel.

For gaining a complete algebraic description of VM-FIRE steel, more load levels at stresses less than 20 MPa would be required to comprehend the elastic range. Furthermore it would be necessary to include temperatures up to 1,200°C and to continue the tests until failure occurs. Nevertheless the authors only expect faint differences to carbon steel so that there is no unconfined recommendation to resume the tests.

4. NUMERICAL SIMULATION OF FULL-SCALE FIRE TESTS

The development of the fire-resistant steel VM-FIRE was accompanied by full-scale fire tests. The test data was used to validate the established material model for fire-resistant steel with the computer program BoFIRE. This code is based on the Finite Element formulation and written by Schaumann [5]. Only the alloy of the last of the three tests (see section 4.1) is completely identical to the material of the small-scale tests presented in section 2. The steel alloy of the first two tests (see section 4.2 and 4.3) was slightly different. Nevertheless, the approach for the material properties was taken for the simulation of all tests.

4.1 Second full-scale fire test performed in Brunswick, Germany

At 11 July 2006 a full-scale fire test on a column consisting out of VM-FIRE steel was performed on behalf of VALLOUREC & MANNESMANN TUBES. It is first presented because the material formulation established in section 2 is based on the alloy used in this test. In comparison to a previous test (see section 4.2) proof load was reduced to N = 770 kN, resulting in a load-ratio of 47%. Moreover, the alloy of the VM-FIRE steel was improved compared to the alloy used in the first test. The static system and cross-section, which are shown on the left side of Figure 5, correspond to the previous test. Mechanical properties and loads are given in Table 3 in the Appendix, where the column is denoted as 'BS-2'. The column failed after 29 minutes exposure to ISO standard fire. The deformed column after test and cooling can be seen on the right side of Figure 5.

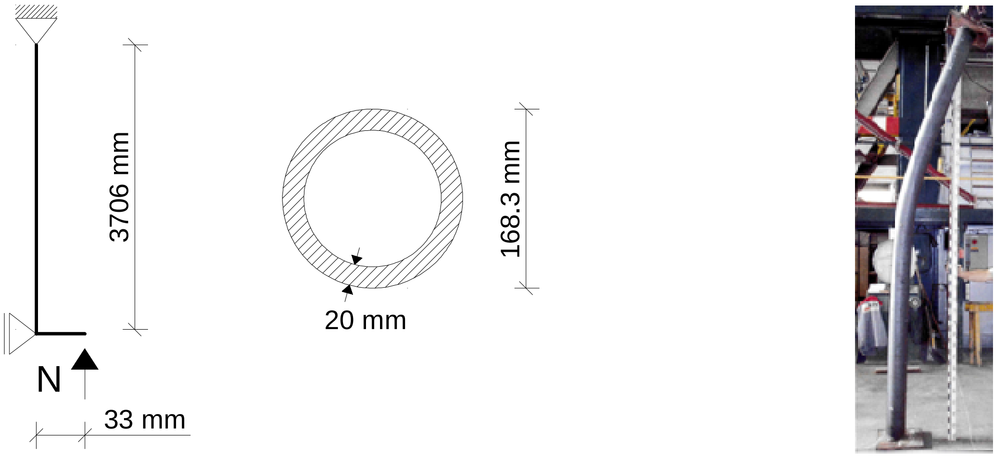

Fig. 5 - Static system and cross-section of the columns tested in 2005 and 2006 (left); column tested in 2006 after fire test (right).

The fire test was simulated using the Finite Element based computer program BoFIRE. Due to the moment resulting from the planned eccentricity at the column end, the imperfection of the test specimen was of secondary importance. Nevertheless its influence was investigated for the following assumed sinus-shaped imperfections, where the actual yield strength of VM-FIRE steel was used in the numerical simulations:

1) L/1,000 = 3,706 mm/1,000 = 3.706 mm
2) L/2,000 = 3,706 mm/2,000 = 1.853 mm
3) No imperfection

With:
L = Length of the column.

Results of the numerical study are summarized in Table 1. It is evident that the magnitude of the imperfection has only slight influence on the computed fire resistance. The actual fire resistance of 29 minutes was underestimated for all calculations, whereas the axial displacement was overestimated with a maximal divergence of 2.9 mm.

Tab. 1 - Results of the second full-scale test in Brunswick, Germany.

Test specimen	VM-FIRE Imperfection L/1,000	VM-FIRE Imperfection L/2,000	VM-FIRE without Imperfection
Measured max. cross-sectional temperature in [°C]	726		
Computed max. cross-sectional temperature in [°C]	*660*	*665*	*670*
Measured max. axial displacement in [mm]	28		
Computed max. axial displacement in [mm]	*30.6*	*30.8*	*30.9*
Tested fire resistance time in [min]	29		
Computed fire resistance time in [min]	*26.3*	*26.6*	*26.9*

4.2 First full-scale fire test performed in Brunswick, Germany

A previous full-scale test was performed at 31 August 2005 in Brunswick. An interim alloy of VM-FIRE steel was used, which was later-on improved for the second fire test in Brunswick. It should be noted that the algebraic formulation developed in section 3 bases on the alloy used in the second test (section 4.1). Apart from that both the static system and cross-section of the second test correspond to the first test (see Figure 5). Material properties and column load can be seen in Table 3. The column was subjected to ISO standard fire and loaded with 850 kN, which corresponds to a load ratio of 55%. It failed after 26 minutes.

The fire-test was simulated with the computer program BoFIRE. Numerical results are to be found in Table 3 in the Appendix (column 'BS-1'). It can be seen that the tested fire resistance of 26 minutes is accurately predicted using the established material properties. The axial displacement is overestimated with a maximum divergence of 4.6 mm. Compared to this, the computation for the same column out of S355 carbon steel led to a reduced fire resistance of only 18 minutes.

4.3 Full-scale fire tests performed in Berlin, Germany

In the year 1999 three unprotected steel columns were tested on behalf of the former German company Mannesmannroehren-Werke AG. Static system and cross-section are shown in Figure 6 along with the deformed columns after testing and cooling. One column consisted out of a preliminary alloy of the fire-resistant steel VM-FIRE (denoted as column 'K1' in the following). The two other columns were constructed out of carbon steel S355 (columns 'K2' and 'K3'). Material properties and loading are summarized in Table 3 in the Appendix.

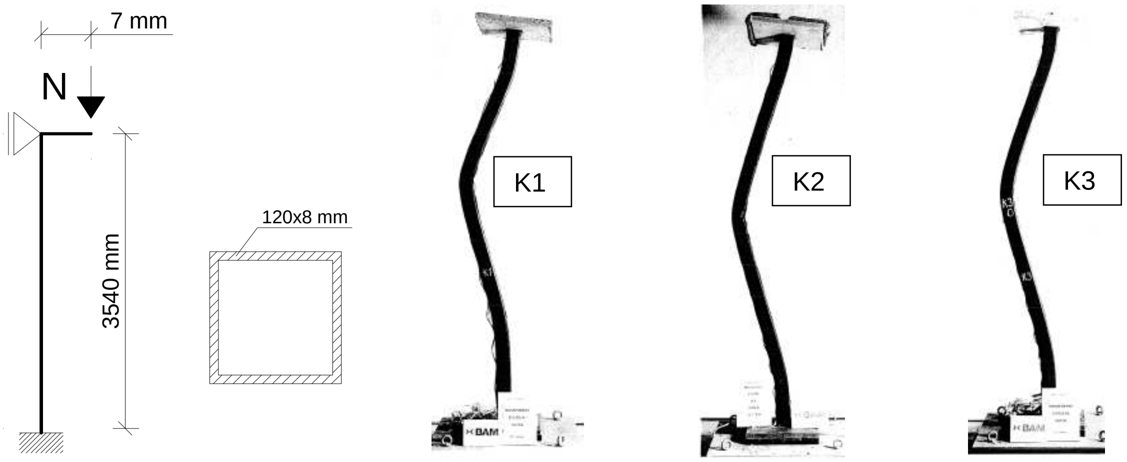

Fig. 6 - Static system and cross-section of the columns tested in Berlin (left); deformed columns K1 to K3 after test and cooling.

All columns were subjected to ISO standard fire until failure occurred. An imperfection of L/1,000 = 3,580 mm/1,000 = 3.58 mm was assumed. Selected results of the fire tests as well as numerical investigations can be found in Table 3 in the Appendix.

The measured cross-sectional temperatures, which are not presented here, exceed the calculated ones from 34°C (column K1) to 45°C (column K3) at most. However, a significant thermal gradient of about 400°C along the height of the column is documented in the test report [6].

This temperature gradient induces thermal bowing and complicates the comparison between experimental and numerical results. As the test data does only include information on axial displacement of the column head but not lateral displacement of the mid of the column, it is not reasonable to assess the effect of the temperature gradient.

Notwithstanding this fact the numerically and experimentally determined fire resistance times stand in excellent agreement with a maximum difference of one minute (column K3). Attention should though be paid to the fact that material properties used for the numerical simulation were established for the second test in Brunswick, Germany. This has to be ascribed to the missing material properties for the preliminary alloy of VM-FIRE steel used in this test in Berlin, Germany.

Altogether the good agreement between numerical simulation and fire tests is nevertheless striking. This can be explained by the fact that the material properties and namely the stress-strain relationship are comparable for small strains. Significant differences only occur for large strains. Since the tested columns were slender and therefore prone to global instability, which is linked with small strains, it becomes scarcely noticeable that the used stress-strain relationship was derived from another alloy of the fire-resistant steel. Therefore it can be concluded that the defined stress-strain relationship allows for sufficiently precise estimations considering column failure at small strains.

5. IDENTIFICATION OF OPTIMAL CROSS-SECTIONAL DIMENSIONS FOR CIRCULAR HOLLOW SECTIONS WITH 30 MINUTES FIRE RESISTANCE

It becomes evident from the previous investigations that columns consisting out of VM-FIRE steel showed considerably higher fire resistance times than similar columns out of S355 carbon steel. The increased fire performance of VM-FIRE steel can be attributed to its superior strength retention. Referring to the right side of Figure 2, the use of the newly developed fire-resistant steel is in particular interesting for cross-sectional temperatures between 500°C and 700°C. In unprotected steel sections, these temperatures are typically attained after 30 minutes exposure to ISO standard fire. Thus, it was the aim to identify optimal cross-sectional dimensions for circular hollow sections constructed out of VM-FIRE steel with cross-sectional temperatures between 500°C and 700°C when exposed to 30 minutes ISO standard fire.

Five different circular hollow sections were numerically investigated. The heating was computed by means of simplified formulae according to [1]. The investigated hollow sections are summarized in Table 2.

Heating of fire-exposed cross-sections is significantly influenced by their section factor ‘A/V’. This is the fire-exposed surface area of the member divided by its volume, both per unit length. High values indicate fast heating and vice versa. Circular profiles should in general be preferred from fire design point of view as their heating is delayed due to their small area of fire exposure [7,8].

Besides an often used cross-sections (line 2 in Table 2), two profiles with high (line 1) and low section factor A/V (line 3) were examined as upper and lower limit, respectively. In addition, two hollow sections were identified where the cross-sectional temperatures after 30 minutes exposure to ISO standard fire attained 543°C (line 5) and 702°C (line 4). For this reason, the latter examples show temperatures within the previously recommended temperature range from 500°C to 700°C. Profiles with cross-sectional temperatures of about 600°C are particularly interesting for the use of VM-FIRE steel and were hence also considered (line 6).

The right side of Figure 7 shows the heating of the different hollow sections exposed to ISO standard fire. It is obvious that the cross-sectional temperatures approximate the gas curve with increasing section factor.

Tab. 2 - Studies on different hollow sections regarding their heating under ISO standard fire.

Line	Circular hollow section	A/V in [m^{-1}]	Characterization
1	101.6 × 4.0 mm	260	Upper limit
2	323.9 × 8.0 mm	128	Standard profile
3	508.0 × 40.0 mm	27	Lower limit
4	323.9 × 20.0 mm	53	Interesting for VM-FIRE
5	323.9 × 40.0 mm	29	Interesting for VM-FIRE
6	323.9 × 30.0 mm	37	Ideal for VM-FIRE

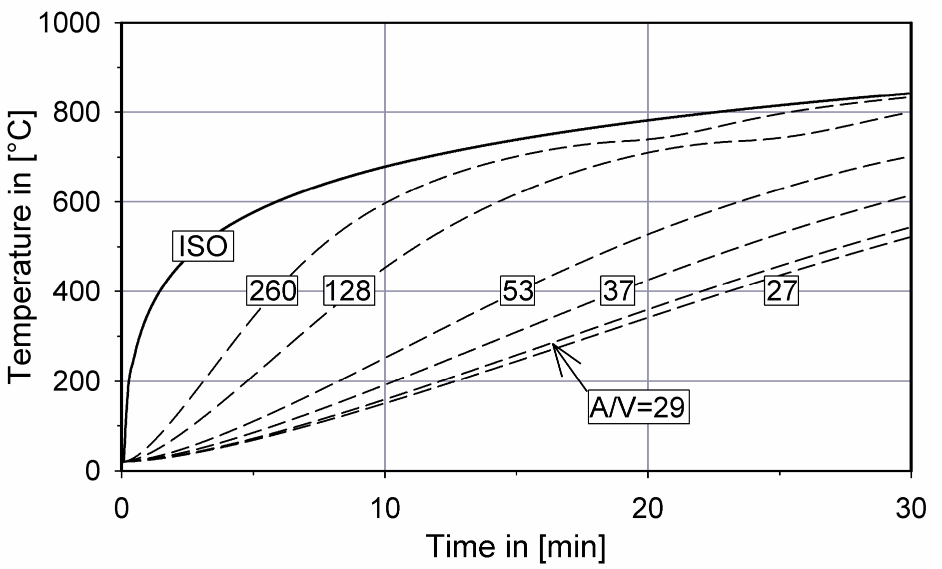

Fig. 7 - Cross-sectional temperatures for different section factors and exposure to 30 minutes ISO standard fire (right).

By means of simplified formulae it was pointed out that a hollow section with dimensions of 323.9 × 30.0 mm is particularly reasonable for the use of VM-FIRE steel. This is confirmed by numerical investigation using the program BoFIRE. The static system is chosen according to Figure 5. Nominal yield strength of 355 MPa is assumed for VM-FIRE steel. The column is loaded with N = 3,500 kN with load eccentricity of 33 mm and imperfection of L/1,000. This results in a load ratio of η = 59%.

The member failed after 39 minutes so that it meets the requirements of fire resistance class R30. The calculation was repeated using the material properties of carbon steel S355. In this case, the column already failed after 26 minutes and thus did not meet the requirements. The investigated columns are characterized by a related slenderness of $\bar{\lambda} = 0.46$.

To study effects of slenderness, the column height was increased to 7 m, which in turn results in a greater related slenderness of $\bar{\lambda} = 0.88$. The other boundary conditions remained unchanged. As concerns the column consisting out of VM-FIRE steel, fire resistance time decreased from 39 to 26 minutes. Thus, requirements of the fire resistance class R30 could not be met. The same column out of carbon steel S355 already failed after 20 minutes. It becomes clear from this simple example that VM-FIRE steel is interesting for compact columns or beams that are not prone to global buckling.

The comparison between slender and non-slender columns underlines the importance of appropriate boundary conditions to benefit from fire-resistant steel. The higher initial costs can only be justified for members that are not prone to stability problems. At large strains, the fire-resistant steel gains high effective yield strength, which exceeds that of conventional steel by far in fire case.

In general VM-FIRE steel is ideal for members where stability problems can be excluded, e.g. compact columns or members in bending, such as beams. A significant increase of the elastic modulus by means of metallurgy can be excluded. Under the provision of large strains it is possible to benefit from the superior effective yield strength of VM-FIRE steel at elevated temperatures.

6. SUMMARY AND OUTLOOK

In this paper a report is presented on material investigations, five fire tests on steel tubular columns and numerical investigations in connection with new fire-resistant steel called VM-FIRE. The research work was carried out by VALLOUREC & MANNESMANN TUBES with scientific support of the Institute for Steel Construction, Leibniz Universitaet Hannover.

The constitutive law of VM-FIRE was derived from transient state tests and implemented in the computer program BoFIRE. Comparison between numerical results and results from five full-scale tests on columns showed that the established material formulation is appropriate to accurately predict the load-bearing behaviour of fire-exposed members constructed out of VM-FIRE steel. Moreover, reasonable range of application for columns with circular hollow sections and constructed out of VM-FIRE steel was identified to meet requirements for fire resistance class R30.

The future market trend for VM-FIRE or other fire-resistant steels does not depend so much on its price. Rough estimates yield in additional 10% to 20% costs compared to conventional mild steel. A short-term availability is decisive for the success. It is completely clear that the wide product range cannot be held up by steel merchants for steel beams and plates. It is therefore important to identify interesting application fields and cross-sectional dimensions. A first step towards this objective was made in this contribution.

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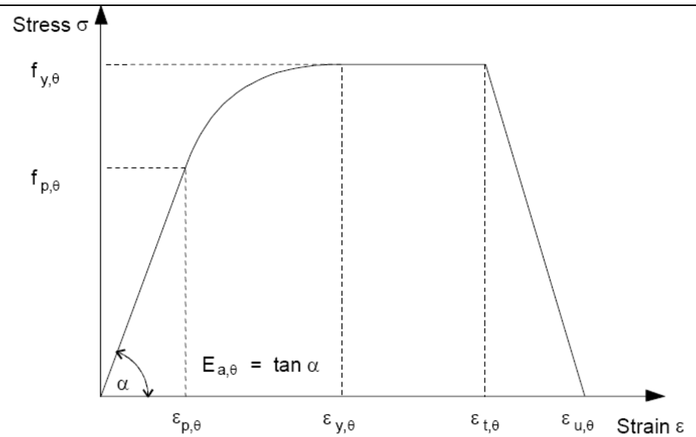
APPENDIX



Key:	$f_{y,\theta}$	effective yield strength;
	$f_{p,\theta}$	proportional limit;
	$E_{a,\theta}$	slope of the linear elastic range;
	$\varepsilon_{p,\theta}$	strain at the proportional limit;
	$\varepsilon_{y,\theta}$	yield strain;
	$\varepsilon_{t,\theta}$	limiting strain for yield strength;
	$\varepsilon_{u,\theta}$	ultimate strain.

Fig. 8 - Stress-strain relationship for carbon steel at elevated temperatures acc. to [1].

Tab. 3 - Test data and numerical results for investigations on large-scale columns.

Test	**BS-2**	**BS-1**	**K-1**	**K-2**	**K-3**
Steel hollow section	Circular 168,3 × 20 mm		Square 120 x 8 mm		
Material	VM-Steel	VM-Steel*)	VM-Steel*)	S 355	S 355
Actual yield strength [MPa]	449	413	610	430	430
Compression load [kN]	770	850	638	638	450
Static system	both ends pin ended		pin ended / fixed		
Length [m]	3.706		3.540		
Eccentricity [mm]	33		7		
Actual load ratio	0.47	0.55	0.55	0.71	0.49
Fire resistance time [min]	29	26	16	12	16
Numerical Simulation					
Material model applied	New VM-FIRE approach			Eurocode approach	
Calculated fire resistance time [min]	27	26	16	12	15

*) *Intermediate alloy*