DEVELOPMENT OF AN INTEGRATED MODELLING METHODOLOGY FOR COMPARTMENT FIRES BY IMPLEMENTING A WEAK COUPLING STRATEGY BETWEEN A CFD AND AN FE SOFTWARE

SVILUPPO DI UNA METODOLOGIA DI MODELLAZIONE INTEGRATA PER L'ANALISI DI INCENDI DI COMPARTIMENTO APPLICANDO UNA STRATEGIA DI ACCOPPIAMENTO DEBOLE TRA UN SOFTWARE CFD E UNO AGLI EF

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ABSTRACT

The article presents the assumptions and the issues that arise when developing an integrated modelling methodology between a Computational Fluid Dynamics (CFD) software applied to compartment fires and a Finite Element (FE) software applied to structural systems. In particular, a weak coupling methodology used to simulate a fire exposed structure by modelling the fire development in the compartment, the heat penetration in the structure and the mechanical response is described. The advantages and the disadvantages of such a technique are highlighted compared to a full coupling that conversely takes into account all mutual interactions. The favourable aspect of computing the thermal response of the structure in the FE model in order to avoid modelling the structure in the CFD model is underlined, namely a sensitive reduction of computational demand. This methodology is particularly suitable for relatively thin steel structures in large compartments. Moreover, the need of a standardised transfer file in order to get the methodology as flexible as possible in terms of versatility is emphasized. Finally, a comparison of two different Cartesian interpolation techniques is shown.

SOMMARIO

L'articolo presenta le ipotesi e le problematiche che sorgono quando si intende sviluppare una metodologia di modellazione integrata tra un software di fluidodinamica computazionale (CFD), applicato a incendi in compartimenti, e un software basato sugli elementi finiti (FE), applicato a un sistema strutturale. In particolare la metodologia basata su un accoppiamento "weak" è descritta nel caso di simulazione di strutture esposte al fuoco per cui si richiede la modellazione: i) dello sviluppo dell'incendio nel compartimento, ii) della penetrazione del

calore nella struttura e iii) della risposta meccanica. Vantaggi e svantaggi di questa tecnica sono evidenziati sulla base del confronto con un accoppiamento "full", che invece tiene conto di tutti gli effetti mutui. Il beneficio di eseguire l'analisi termica nel modello FE in modo da evitare che la struttura sia modellata nel modello CFD è mostrato come pure la sensibile riduzione dell'onere computazionale. Questa metodologia è particolarmente adatta per strutture in acciaio in grandi compartimenti. Inoltre, è enfatizzata la necessità di un file di trasferimento standardizzato in modo da rendere tale metodologia la più versatile possibile. Infine, viene presentato un confronto tra due tecniche di interpolazione Cartesiana.

1 INTRODUCTION

Integrated modelling methodologies applied to compartment fires in order to obtain the thermo-mechanical response of structures exposed to fire would represent a powerful tool to widen the application field of structural fire safety engineering by overcoming limitations associated to simplified procedures. The exploitation of such strategies based on the coupling between CFD and FE programs are already used in medicine for modelling the blood flow in arteries [1]. However, in the fire engineering field, very few applications are available and the ones that have been developed are often limited to specific software pairs [2]. The Research Fund of Coal and Steel (RFCS) project called FIRESTRUCT [3] dealt with this issue by studying different coupling approaches and employing several software. The generalised and standardised formulation of a transfer file in a weak coupling strategy that is not necessarily bound to the choice of specific software was found to be one of the most practically applicable approaches. This paper describes the main features, advantages and limitations of this approach.

2 OVERVIEW ON THE INTEGRATED CFD-FE METHODOLOGY

2.1 Compartment fires: problem definition

Three problems have to be solved when modelling the behaviour of a structure subjected to a compartment fire, each of them being governed by different physical phenomenon and, hence, by different equations: 1) temperature development in the compartment; 2) thermal response of the structure and 3) mechanical response of the structure. The fire development analysis allows getting the temperatures of gasses and the radiative and mass flows in the compartment; by means of the thermal analysis, the temperatures in the structural elements are obtained; the mechanical response provides the behaviour of the structural system, i.e. stresses, deflections etc.,. Several differences distinguish these three processes. First, the spatial scale of the thermal analysis in the structure is an order of magnitude smaller than the spatial scale used for the compartment temperature development and the mechanical response. Second, the time scale may be different to solve the problem within CFD and FE. Third, for the temperature development in the compartment and the mechanical response a 3D analysis is generally required, whereas for the thermal analysis a 2D analysis is usually sufficient. Thus, some issues arise when an integrated methodology CFD-FE is to be used to tackle the whole problem. It is natural to assign the task of performing the compartment temperature development analysis to the CFD model and the mechanical response to the FE model, but it is not so straightforward to decide where to carry out the thermal analysis. Both software may be exploited to fulfil the task. The advantages to perform the thermal analysis in the CFD model are first to get direct information from the compartment temperature development analysis and, second, to allow consideration of the energy absorbed by the structure to be considered in the analysis of the compartment. On the other hand, if the thermal analysis in the structure is carried out in the FE model, all data necessary are directly available by the FE code to determine the mechanical response. Whatever the choice, the difficulties arise when data have to be exchanged between the two software, because of different scales in space and time. Moreover, if the thermal analysis is performed in CFD software, the compartment model must include the structure as well. The latter aspect is not desirable as described later on.

2.2 Levels of coupling

From the description of the problem it is clear that coupling CFD to FE model is far from straightforward and that the selected level of coupling influences the complexity of the model. In reality all three problems are mutually coupled (full coupling or two-way coupling) as shown in Fig. 1 and reported in Table 1 where the main phenomena involved in a compartment fire are listed along with their mutual interaction.

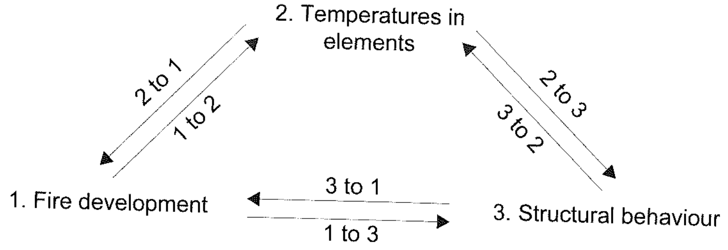

Fig. 1: Full coupling strategy between the main phenomena involved in a compartment fire.

Table 1: Mutual interactions of main phenomena involved in a compartment fire.

	COUPLING					
	1 to 2	2 to 3	3 to 1	1 to 3	3 to 2	2 to 1
FIRE						
Convection and radiation to structural elements	x					
VELOCITY OF GASES						
Convection factors	x					
Dynamic pressure on walls, windows				x		
PRESSURE						
Static pressure on walls, windows				x		
TEMPERATURE IN MATERIALS						
Thermal elongation of elements		x				
Degradation of mechanical properties		x				
Absorption of energy from the compartment						x
PLASTICITY AND CRACKING IN ELEMENTS						
Generation of heat or heat leakage			x		x	
Modification of material thermal properties					x	
DISPLACEMENTS IN ELEMENTS						
Modification of the gas flow			x			
Modification of the element thermal exposure					x	

The implementation of a full coupling allows taking into account all phenomena and it guarantees a general field of application as well as a solution that tends to be exact. An example of full coupling is the interface developed between VESTA, a CFD software, and DIANA, an FE software developed by TNO in the Netherlands [3]. However, an integrated methodology that relies on full coupling is very complex to achieve. The first reason lies in various uncertainties that question the so called exactness of the method. For instance, heat leakage through cracks in concrete or gypsum plaster boards enclosures are still very difficult to quantify because they do not follow deterministic rules. Moreover, from a programming point of view, the code of the selected CFD software and the code of the FE program have to be modified so that they can communicate for the exchange of data, but it means that in most cases the integrated methodology will not work if another CFD or a another FE software is used. This is a clear drawback in terms of versatility and flexibility. Furthermore, for each simulation, a CFD specialist as well as an FE specialist are required since the two models cannot be run independently. Other typical issues that may occur in the design practice are related to possible modifications that the structure undergoes during the construction project as well as modifications of the structure that have to be applied because of an unsatisfactory behaviour in terms of fire safety requirements. Since the structural elements must be included in the CFD model, any changes in the structural system imply that the whole analysis must be re-run, entailing large time consuming analyses.

From these consideration, a simplified approach, the so-called weak coupling, is proposed to overcome the major aforementioned issues with the aim be applicable to a wide number of likely-to-occur scenarios in compartment fires.

3 PROPOSED WEAK COUPLING METHODOLOGY

3.1 Assumptions and general remarks

In the proposed weak coupling (or one-way) approach the mutual interactions are discarded, as illustrated in Fig. 2. The CFD software models the fire development, while the FE program performs the thermal and the mechanical analyses. The fire development is calculated independently of the thermal response in the linear elements of the structure such as, for example, steel columns, beams or truss girder. If part of the structure is made of planar elements that also constitute boundaries of the compartment such as, for example, concrete walls or slabs, they must be modelled, perhaps with some degrees of approximation [4], in the fire development analysis. The detailed temperature field in these structural elements will nevertheless be computed subsequently by the FE software. As a consequence, if p variations of the structure must be evaluated under q fire scenarios, only q CFD analyses have to be performed, compared to $p{\cdot}q$ coupled analyses in a full coupling approach.

In this strategy, the thermal response of the structure represents the input of the mechanical analysis. Hence, it can be performed first, over the whole time domain, and then the resulting data are transferred at the beginning of the mechanical analysis which is performed subsequently.

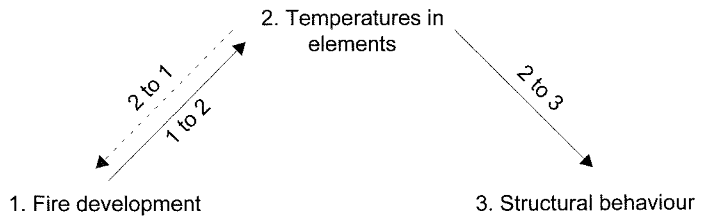

Fig. 2: Weak coupling strategy between the main phenomena involved in a compartment fire.

Nonetheless, these simplifications imply some limitations:

i) the dimensions of the structural elements and their displacements perpendicular to their longitudinal axis must be small compared to the dimensions of the compartment in order not to significantly influence the temperatures and the air flow around the elements. For instance, a 1x1 m^2 concrete columns in a 100 m^2 compartment must clearly be considered in the CFD model. This would also be the case for 1 meter deep concrete beams in a car park with a distance from the floor to the beams that is on the order of magnitude of 2 meters. Very flexible structures that are sensitive to air pressure variation are also not suitable for such integrated methodology because the effects of air pressure variation cannot be neglected.

ii) irrigated structures in which water is circulating in order to keep the temperature of the structure within acceptable limits cannot be neglected because they may contribute in evacuating important amount of energy from the compartment.

This procedure is thus particularly well adapted for metallic structures made of relatively thin members (frame, truss girders) and located in very large compartments (railway or airport entrance halls, exhibition halls) where a localised fire is developing and simplified thermal models, such as those proposed in Eurocode 1 [5], cannot be employed because the geometry of the compartment is too complex or the position of the structure in the compartment or with respect to the position of the fire is not within the field of application of simplified model; the latter in fact principally yield either a heat flux underneath an horizontal ceiling or the temperature in the centreline of the plume of a localised fire.

3.2 How it practically works

In this section, the practical issues that have to be solved when implementing such an approach are presented. The programs used in this paper to illustrate the proposed integrated methodology are FDS [6] and SAFIR [7]. The main steps necessary to integrate a CFD program and an FE program are :

1) at the end of the CFD analysis, a transfer file containing all information regarding the fire development, i.e. temperature of gas, convection factors and radiant intensities, has to be produced. These quantities can be provided at each grid point of the CFD model (the grid that was required to allow a precise determination of the solution) or instead at grid points of a coarser mesh reckoned by the CFD user as sufficient to get a sufficiently accurate representation of the solution that has been obtained.

The format of the transfer file should be as standardised as possible so that in a future perspective it could be used for any choice of CFD and FE software. Hence, type of file (e.g. ASCII), syntax, type of reference system, type and format of numbers, presence of blank lines etc. have to be clearly stated. Such a format has been proposed within the FIRESTRUCT project and can be obtained from the authors. Radiant intensities are preferred to radiant fluxes because the structural elements are not included in the CFD model and thus no information is available at that stage about the shape of the cross-sections. The fluxes at the surface of the structural elements will be computed within the FE software by integrating the radiant intensities which allows taking into account possible shadow effects.

2) A 3D Cartesian spatial interpolation is needed because the points of the structure where the information is needed (called here “the structural points”) generally do not coincide with the points of the CFD grid. Thus, an interpolation algorithm is required to get information about the fire development at the structural points on the basis of the structure position in the compartment. A trilinear interpolation algorithm has been successfully implemented by the authors to fulfil this task.

3) An interpolation in the time domain is also necessary because the time steps of the CFD analysis and the time steps of the thermal analysis may not be the same. In this case a simple linear interpolation may be used.

4) In order to get the impinging fluxes q on the surface of the structural elements a spherical numerical integration of radiant intensities I has to be performed, see Eq 1.

$$q = \int_{2\pi} I \cos\vartheta \, d\omega \qquad (1)$$

Where $d\omega$ is the elementary solid angle and θ the angle between the elementary solid angle and the normal to the surface.

But generally the directions of the intensities which are required to perform the spherical integration are not the directions in which the intensities are given by the CFD analysis. This is particularly the case if the structural elements are not parallel to the axes of the system of coordinates used in the CFD analysis (e.g. for diagonals in a truss girder) A spherical interpolation is thus performed in order to obtain the radiant intensities in the directions required by the numerical integration. Rotation of local axes are required to find the surface system of coordinates taking into account the direction of the longitudinal axis and the shape of the cross-section. In order to perform the spherical interpolation a CSS grid (Cubic Spline Sphere GRIDder) algorithm has been used here. CSS schemes are specifically designed for interpolation on a sphere; the one used here is based on the work of Renka [8].
It is essential that the type of mesh and type of system of coordinates used in the CFD analysis (step 1) be clearly defined and taken into account in steps 2 and 4. The format of the transfer file established within the FIRESTRUCT project is based on the hypotheses of a structured parallelipedic mesh in a dextrorsum Cartesian system of coordinates. The position of the origin of the system of coordinates and the directions of the "X", "Y" and "Z" axes as well as the direction of gravity must be common in the CFD and in the FE analyses.

4 PRELIMINARY TESTS ON THE CARTESIAN INTERPOLATION

The FDS-SAFIR interface that is being developed relies on a trilinear interpolation algorithm in order to perform the spatial Cartesian interpolation. It provides exact values of the field to interpolate when a structural point coincides with a CFD grid node.
In a first phase, it had been envisaged to use a more sophisticated algorithm based on the concept of natural neighbours [9]. Some tests were performed in order to compare the two algorithms for functions that are likely to represent temperature fields or distributions of radiant intensities in a compartment fire. For example, an exponential function was used to simulate a two-zone temperature field in a compartment 3 m long by 3 m high discretised by the mesh illustrated in Fig. 3. The function used to model the temperature along the height of the compartment reads (Eq. 2)

$$T(y)=200-100\left(1-e^{10y-15}\right)\ \text{if } y<1.5\text{ m}$$
$$T(y)=200+100\left(1-e^{-10y+15}\right)\ \text{if } y\geq 1.5\text{ m} \qquad (2)$$

with y the distance from the floor.

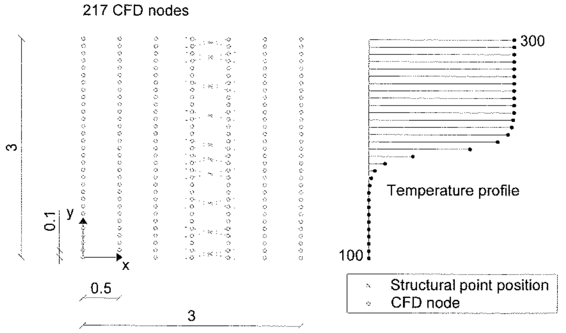

Fig. 3: Two-zone scenario: CFD mesh and temperature profile.

Also, a Gaussian distribution function was used in order to model the intensity along one direction coming from a localised fire (see Figs. 4 and 5). The equation of the function is

$$I(x,y)=100\left(1+\frac{1}{0.25\sqrt{\pi}}e^{-(y-2)^2/0.25^2}\left(\frac{2}{3}x+1\right)\right)\ \text{if } x<2\text{ m} \qquad (3)$$
$$I(x,y)=0\ \text{if } x\geq 2\text{ m}$$

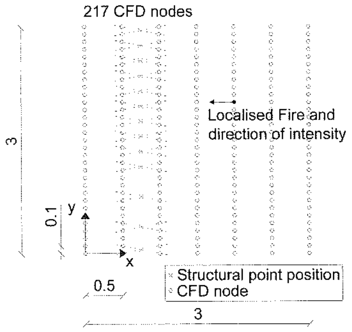

Fig. 4: Localised fire: CFD mesh.

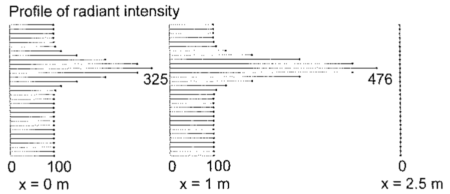

Fig. 5: Localised fire: profile of radiant intensities.

The error of the interpolation for both cases is shown in Figs. 6 and 7 where it is possible to observe that the trilinear interpolation always provides more accurate results.

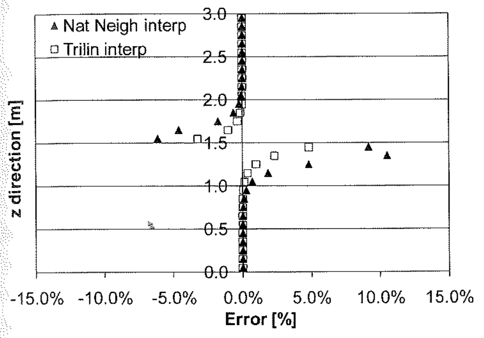

Fig. 6: Two-zone scenario: comparison of the error between interpolation algorithms.

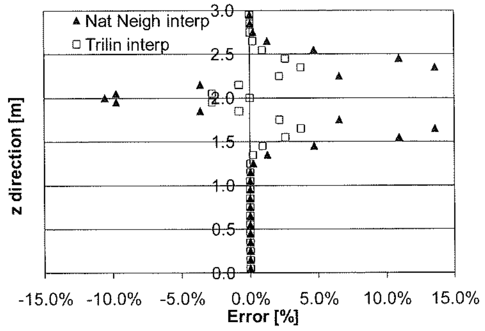

Fig. 7: Localised fire: comparison of the error between interpolation algorithms.

5 CONCLUSIONS

This paper describes assumptions and issues of an integrated modelling methodology for the behavior of a structure located in a fire compartment by implementing a weak coupling approach. This strategy allows to perform the fire development analysis independently from the thermal analysis of the structure and from the mechanical response analysis by neglecting the structural elements in the CFD model. Hence, it results to be suitable for localised fires in very large compartments built with relatively thin structures where the transverse dimensions of the structural elements can be neglected. The existence of a standardised transfer file used to communicate the data between the CFD and the FE software is fundamental to guarantee versatility of the strategy. Preliminary tests on two Cartesian interpolation algorithms showed that the trilinear interpolation provides better results in terms of accuracy compared to a natural neighbours based interpolation.

ACKNOWLEDGMENT

The financial support of Arcelormittal and of the Province of Trento through the Call 3 - post-doc 2009 (Outgoing) - FIRAS project are gratefully acknowledged.

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KEYWORDS

Fire engineering, integrated methodology CFD-FEM, compartment fires, cartesian spatial interpolation, steel structures