

STRUCTURAL RESPONSE AND DETAIL

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ABSTRACT

This paper is an overview of the main results obtained in work package 4 “Fire Effects and Tunnel Performance: System Structural Response” of UPTUN Project and a summary of the general engineering outcomes drawn out from the performed research work. It describes task by task the main engineering conclusions and especially recommendations for an upgrading of a safer structural behaviour in existing tunnels.

1. WP 4 OBJECTIVES

1.1 Main objectives

The main objective of WP4 was to define, develop, assess and promote new methodologies and innovative materials / technologies to eliminate and or at least reduce the risk of an unacceptable behaviour of the structural systems of a tunnel. WP4 aimed at obtaining: i) assessment of the performance of the integral tunnel structure in all fire phases, from ignition, through growth to the fully developed stage and the decay period; ii) optimisation of the thermal and structural behaviour of all tunnel components designed for active and passive safety; iii) increase of load bearing capacity under accidental conditions; iv) reduction and limitation of non operational time and repair retrofitting work; v) evaluation of existing technology with main emphasis on cost-benefit (including maintenance); vi) establishment of methods for safer design and evaluation and recommendations for optimal tunnel systems¹.

1.2 WP 4 Tasks

WP4 work has been divided into the following 5 Tasks: Task 1 – Structural Concrete Components, Task 2 – Functional Elements, Task 3 – Damage / Repair and Recovery, Task 4 – Structural (Material / Design) and Innovation, Task 5 – Safety Criteria and Recommendation.

The proposed measures derived from the Tasks developments cannot be expected to solve the problems of the whole infrastructure system, but are designed to mitigate some of the problems connected with different fire scenarios, especially in the areas connected to repair-recovery cost-effective methodologies and the availability of procedures to assess spalling risks. As far as the first point is concerned a reduction of the non-operational time for a tunnel damaged by a fire accident is obtained by the use of new quick damage level assessment methods and repair-recovery procedures defined and set up as part of the WP4 research work. This will have a considerable socio-economic impact.

Regarding possible spalling occurrence and relevant damage part of the main outcome of WP4 is in the area of innovative materials and methodologies to prevent and reduce risks of spalling effects. For this purpose, both testing and advanced software capabilities developments have been performed. These tools are the basis for the production of simplified design criteria or recommendations to limit the possible occurrence of spalling effects on materials.

2. TASK 1 STRUCTURAL CONCRETE COMPONENTS

2.1 Objective of the Task

The objective of task 4.1 has been to provide an improved understanding of the fire behaviour of concrete elements which can have a load bearing function and/or a fire separating function. The results have been used by other WP4 tasks and by WP5 and WP6. Moreover they provide assistance to engineers in their daily practice of making a tunnel fire design and the assessment of that design.

2.2 Outline of the performed work

Task 4.1 has been subdivided into several activities, among which the following ones: i) determination of load bearing and / or separating concrete elements behaviour through an in-depth study on real fire incidents and fire tests; ii) experimental examination of one typical critical concrete element; iii) numerical assessment of some critical concrete elements including the specimen of the experiment; iv) comparison of numerical and experimental results; v) mutual comparison of numerical results; vi) recommendations for fire design and for the assessment of critical concrete components.

Special emphasis has been put on the mutual comparison of the numerical studies undertaken by various partners with different software packages to come up with recommendations for numerical modelling.

2.2.1 Functional requirements Load bearing function

When the tunnel is constructed through soft soil, the tunnel lining has to bear substantial loads, such as water pressures and dead weight of the soil and in case the tunnel is located near the surface also point loads act on it caused by the constructions built on top of the tunnel. When the tunnel passes through rock type of ground, the tunnel lining does not have to bear considerable mechanical loads. Nevertheless, a lining is generally applied to prevent erosion of the surface and water leakage. Also other concrete elements can have a load bearing function, such as intermediate columns or walls (see Figure 1).

During fire, the load bearing structure needs to maintain its function for at least the time that the users need to escape and the rescue teams need to suppress the fire and rescue the users. In addition, it is often not allowed that the load bearing structure collapses as the social-economic consequences are estimated to be unacceptable. The load bearing capacity will be lost when a failure mechanism occurs. Typical failure mechanisms are: i) bending failure, ii) anchorage failure of the reinforcement; iii) shear failure; iv) punching shear failure; v) buckling failure.

During fire, the concrete components are heated which causes damage in concrete. For concrete, three main damage processes are: i) chemical degradation of the constituents, caused by the locally attained temperatures, ii) irreversible deformations such as thermal

cracks and slip of the reinforcement, caused by thermal stresses. Thermal stresses are the result of incompatible thermal expansions over the entire construction; iii) spalling, caused by internal stresses such as thermal stresses and vapour stresses. Various types of spalling exist. Damage does not necessarily lead to collapse, but it reduces the load bearing resistance against the various failure modes. Also without collapse, the social-economic consequences of damage might be so high that the acceptance of it is limited.

Thermal stresses can also have a beneficial effect on the resistance against various failure modes. Concrete is a brittle material with a far greater compressive strength than tensile strength. If the thermal expansion of an exposed concrete component is restrained, a beneficial compressive force develops in this component which can significantly improve the load bearing resistance.

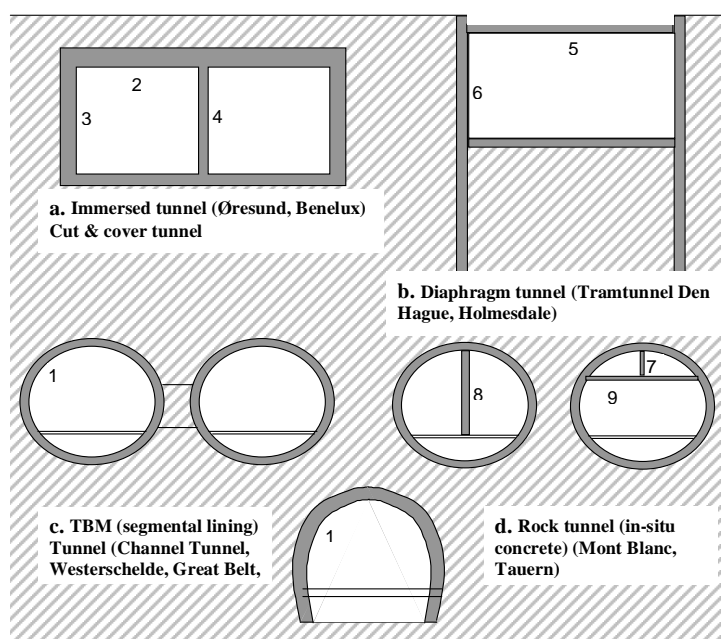


Figure 1. Various types of tunnels and their structural concrete components

As a drawback, the restraining construction is also loaded by those restraining forces which might lead to premature failure of the restraining construction even if this construction is not exposed to fire itself.

In statically undetermined structures, thermal gradients lead to a shift in the bending moment distribution, leading to a rapid development of plastic hinges at intermediate supports. To prevent premature failure at these hinges, sufficient rotation capacity needs to be provided at these supports. In doing so, failure is postponed until also plastic hinges in between two supports have formed.

2.3 Engineering Comments and Advises

Several design arrangements were considered in the parametric study: ceiling with and without bottom thermal shielding and symmetric or asymmetric thermal loading. The study was limited to a single geometry, therefore it is not possible to make any general design recommendations for the suspended ceiling structures, but it is possible to state the following observations: i) the suspended ceiling has a higher resistance to fire if a symmetric temperature loading is applied; ii) this means it is advantageous if the ducts above the suspended ceiling are not used for smoke ventilation; iii) the 20 mm thermal shielding

prolonged the collapse time by 30%, i.e. 30 minutes; iv) the detailing of the edge support shows to be of high importance as it determines the development of dominant restrained forces. The position of the restraining force relative to the neutral axis of the ceiling determines whether the restraint enhances the fire resistance or weakens the fire resistance. It is recommended to either avoid restraining forces or to make sure that the restraining force acts at the lower side of the neutral axis, in order to generate a bending moment in the ceiling that counteracts the applied vertical loads; v) collapse can be postponed beyond the occurrence of plastic hinges for hours, provided that the rotation capacity at the location of the plastic hinges is sufficient; vi) the load distribution changes strongly during fire. In order to ensure plastic behaviour, the anchorage length of the reinforcement needs to be designed for all possible envelopes of the load distribution, i.e. assuming both zero applied load and the design load. The hangers of the vertical wall need to be able to carry the entire load corresponding to a bending moment distribution with plastic hinges at the slab to wall connection.

3. TASK 2 FUNCTIONAL ELEMENTS

3.1 Objective of the Task

The objective of task 4.2 has been to find the design solutions which guarantee the correct function of the rescue and evacuation processes from a tunnel subjected to accident by means of preservation of the functional characteristics components relevant to safety. The investigations have been concentrated on emergency doors, cables, signs and indicators. The data obtained showed the functional capacity of each type of equipment and the limits of functional reliability. Accompanying numerical simulations gave the conditions outside the realisable conditions of the tests. Thus it was possible to determine the functional capacity of each of the equipment under severer conditions.

3.2 Outline of the performed work

Within a tunnel there are a number of functional components which are assumed to operate properly also in case of a fire incident. Among them there are a number, which are of great importance for rescue purposes as well as for protection of the tunnel structure. In case of failure of these elements, the fire may cause serious damages of the tunnel structure and may also lead to great danger for human lives. One activity of this task therefore was to identify the most critical functional components, which should be subject to testing. Due to limitations in resources and budget not every individual component could be tested. Concerning the functional elements identified as being critical for the safety of a tunnel, the partners agreed on the following list of elements for testing: i) all kinds of cables, since they provide energy for the operation of most elements and they transport all kinds of signals, which should be further processed and are the basis for the planning of emergency measures in case of fire incident; ii) the escape doors and protecting doors in general; these elements are necessary and important for the rescue of people in case of fire incident and to protect important installations. The Mont Blanc fire showed this dramatically; iii) for rescue purposes it is important to guarantee that as many people as possible are able to find and use self-rescue routes; therefore the indication of those routes and the guidance to them should operate as long as possible in case of a fire incident. We are talking here about emergency signs, emergency exit indicators and the indications of the way to them.

Another element in a tunnel installation is a ventilation system. Those elements are also seen as being critical. However, ventilation systems are by far the best-known elements in a tunnel installation. A redundant installation guarantees functionality in case of failure of parts of the installation. Therefore the partners in WP4 agreed to not test elements of a ventilation system.

3.2.1 Numerical simulations

A numerical simulation of the test facility of DMT was performed by University of Padua, Italy. The purpose was to obtain data on expected temperatures inside the testing tunnel outside the possible experimental range. The results should be used to extrapolate the test results in order to come to estimations of the behaviour or functionality of the tested equipment under such conditions.

The simulation was carried out using a simplified model, however the results are in good agreement with provided experimental data. It can therefore be assumed that the results of the calculations for conditions outside the experimental range will also be reasonable. Temperature profiles have been provided for fire loads of 40 and 80 MW at 10 and 25 distances downstream of the fire.

3.3 Engineering Comments and Advises

The tests investigating functional elements of tunnel installations were very successful. Although the test program had limited resources available a substantial amount of important results could be obtained.

The tests with the emergency doors showed that under the conditions possible in the test site the samples fulfilled their functional capacity. No leakages or other damages were recorded. The doors are able to protect people properly under the mentioned conditions. At bigger fires and severer conditions the situation will likely become worse. However, the conditions in a real tunnel installation are also very different from the ones at the test site. In most cases the conditions in the vicinity of doors will be less severe than in the test site due to the much larger cross-section of a real tunnel.

The tests with signs and indicators showed that the most important functionality, the visibility, is highly affected by smoke production and distribution within the tunnel. The visibility of each sample under investigation was lost after a few minutes if the smoke front was able to propagate to the installation points. The operability of the samples having electric lights was better than those without. The latter were also highly affected by soot coverage. In general the ventilation system has big influence on visibility of signs and indicators.

Finally the test with different types of cables provided some useful indications about their operability. The limits of operation could be retrieved under the conditions present during the test. However, the results are limited to these conditions only.

4. TASK 3 DAMAGE / REPAIR AND RECOVERY

4.1 Objective of the Task

The objective of task 4.3 has been to provide an improved understanding of damage evaluation methods after fire and knowledge concerning repair of materials. This is done in order to define a methodology for a low cost quick refurbishment of tunnel after fire.

In accordance with this aim, the specific objectives were to define, qualify and propose a quick low cost in situ damage assessment method and to develop and qualify a shotcrete for repair and recovery.

4.2 Outline of the performed work

Task 4.3 has been organized into several activities: i) in situ methodologies, ii) theoretical analysis, iii) mixes & procedures, iv) prenormative recommendations, v) assessment & innovation. The research technical work was aimed at performing: a) evaluation of the approach to some real case about damage evaluation and material restoration, b) proposition of new NDT methods, c) development of concrete materials for tunnel applications, d) recommendations for the evaluation of the damage and repair executions. The effort spent in task 3 producing 11 technical reports, arrived at the release of contributions M4.1, M4.3 and at the editing of D4.2 and D4.5.

The work started with a critical evaluation of the approach and methodology used to assess the damage level in the various real fires happened in the last years in Europe tunnels. An assessment of the procedure followed in the rehabilitation of damaged tunnels (Great Belt Railway Tunnel, Channel Railway Tunnel and Mont-Blanc Road Tunnel) was carefully revised. In situ damage assessment were used as follows: 1) Core test estimate the strength of in situ concrete by testing cores cut from the structure; Schmidt hammer test gives a measure of the surface hardness of the concrete; 2) Ultrasonic pulse velocity test gives the fundamental relationship between pulse velocity and dynamic elastic modulus and the pronounced temperature sensitivity of this latter parameter; Windsor probe involves shooting a steel probe into the surface of the concrete; 3) Thermo-luminescence tests are based for investigation of fire-damaged concrete on the measurement of the residual thermo-luminescence in small samples of sand drilled from the concrete; 4) Carbonation test, from which useful information on the residual durability of a structure after a fire can be obtained by plotting the carbonation depth for building of different age a few years after being exposed to different degrees of fire damage; 5) Chemical analysis, used to find the residual combined water in hardened cement or residuals of chloride in the concrete, from the relation between the residual combined water contents and the maximum experienced temperature, the temperature outline and also the reduction of strength can be estimated; 6) X-ray diffraction analysis (XRD). Multiple XRD patterns of mortar samples exposed to increasing temperature in the range 100-1000°C show the gradual reduction in Ca(OH)_2 content, indicating gradual deterioration in concrete quality; 7) drilling resistance method, a promising technique, allowing to continuously “scan” the material response at increasing depth. The most interesting feature of this technique is that the deep virgin material is inspected in the final stage of the drilling process. Hence, a reference drilling resistance is available for each test and no special calibration curves are needed for the evaluation of the thickness of damaged concrete.

4.3 Engineering Comments and Advises

It is quite evident the importance to limit the damage consequences, possible catastrophic collapse of the structures and especially human losses. Anyhow similar attention has to be dedicated to the important item aimed and reducing the non-operational time of the tunnel socio-economic impacts such as: i) Cost of structural damage to the users/operators arising from the cost of repairs and the loss of income during the shut down of the tunnel operation (e.g. Channel Tunnel fire); ii) Impact upon the local and national economy from the closure of the facility (e.g. Mont Blanc fire); iii) Social impact of tunnel shut down; iv) Environmental

and economic impact (pollution, noise, vibration, longer and unsuitable route) from the route deviation of vehicles.

Particular effort has been given to the definition, production application and verification of new concrete materials and quick-economic in-situ damage assessment methods. A rapid reinstatement of a functional tunnel can be obtained by the use of new quick damage level assessment methods and repair-recovery procedures, which have been defined and set. This has clearly pointed out a considerable socio-economic potential. In order to guarantee immediate reaction to a fire accident it is vital to know the tunnel design and structure and to understand the function of the various structural elements. It is quite important to have immediately after the fire accident the availability and the action of a qualified person with a complete knowledge of the tunnel. This knowledge could be provided by the nomination of an expert for every tunnel in operation, preferably a person from the design team, to be contacted in case of fire. The procedures to set up and administrate such an expert panel for every tunnel could be the target for future investigations. As an important innovative result an anti-spalling concrete material has been defined, developed and produced. New materials were developed for resistance of fires with less damage and with less repair. Moreover important task 3 outcomes are: a) New methodologies for in situ damage assessment; b) Definition and producing of innovative low cost shootcrete materials for repair/recovery; c) Suggestion about procedure / methodology for repair/recovering tunnel after fire.

While every tunnel represents a structure on its own there are certain characteristics which all tunnels will have in common. These common functions of all tunnels would allow developing guidance for a structured approach for the development of a tunnel repair methodology after a fire event. Even if based on different national standards a common approach could be developed to guarantee a similar strategy within the European nations to be applied after a tunnel fire. This could also help to avoid conflicts in the approach for a large number of tunnels crossing nations borders.

5. TASK 4 STRUCTURAL MATERIALS AND DESIGN

5.1 Objective of the Task

The objectives of the task have been: i) to assess the performance of the integrated tunnel structure in all fire phases conditions; ii) to propose innovative solutions to reduce and/or prevent high damage and possible spalling occurrence of tunnel concrete lining under fire; iii) to improve fire safety in tunnels applies to both the safety of people and the safety of structures.

The fire safety design of tunnels has traditionally provided a higher priority to the issues relating to the safety of people, since the latter is considered merely as an economic issue. Nevertheless, structural integrity in fire does impact upon people in a number of ways (e.g. Heavy objects and/or hot spalled concrete falling on people, flooding when the tunnel lining is breached). In addition there are the financial and socio-economic impacts (e.g. costs of repair/loss of service, impact upon the local and wider economy).

Clearly a fully comprehensive treatment of this subject required joint effort with numerical modelling and theoretical studies. It should be noted that this work is innovative and conducted for the first time. Measures to prevent spalling are then presented.

5.2 Outline of the performed work

The first action was an analysis and a critical check up of the available software for thermal-structural simulation. In particular a summarising report describing the main features of these tools was produced. A careful analysis of the further capabilities development to be introduced in the existing software HITECOSP, so to improve and optimise its spalling risk simulation/prediction (possible occurrence risk) was performed².

Simulation capabilities were introduced and verified for various spalling items, parameters and features (fibre presence, spalling index, thermo-chemical variation in high temperature, ...). Spalling criteria were developed and qualified. At last spalling risk was detailed and defined by design abacus. An investigation of thermal barriers was carried out. With this aim a scrutiny and evaluation of products available on the market for providing an efficient thermal barrier for reducing or preventing explosive spalling was carried out. The following actions were completed: a) Produce a list (excel sheet) of manufacturers which have a product for use as a thermal barrier (name, address, tel, fax, email, contact person etc), b) Make a questionnaire and send it out, c) Evaluate answers to the questionnaire and make a review of barriers.

Risk of occurrence of spalling in tunnels depends upon multiple interacting factors. Historical evidence from real fire in tunnels and buildings supported by experimental evidence in the large and medium-small scale indicate different risk factors depending upon: i) The material itself (e.g. permeability, moisture content, aggregate, thermal expansion), ii) Shape and size of the concrete in question, iii) Moisture boundary condition, iv) Loading condition, v) Heating condition (fire scenario – heating rate, maximum temperature, cooling), vi) Tunnel condition (traffic, geometry, ventilation etc.). Essentially, an expert assessment was carried out for the risks of spalling and the following types of spalling: a) Aggregate Spalling (popping sound), b) Corner Spalling (non-violent), c) Surface Spalling (violent - cracking sound), d) Explosive Spalling (violent - loud bang), e) Sloughing-off spalling (non-violent), f) Post-cooling spalling (non-violent).

It should be re-iterated that there does not exist a clear cut demarcation line between the different types of spalling and that the operative mechanisms will also not be clearly differentiated. However, the categorisation of spalling with their own dominant causative factors may help towards explaining some of the confusion that has existed regarding spalling and may be a convenient method of identifying spalling in practice, understanding it and categorising it as far as is possible. This may be helpful but should not be taken too literally. In addition, an example of a real tunnel has been considered and the risk of spalling given the material used and traffic conditions is also made, as a second stage of this work. Finally the engineering tunnel structural configuration influenced by spalling is examined and preventive measures presented.

5.3 Engineering Comments and Advises

The unexpected damage caused to a concrete construction by spalling can render fire safety design calculations inaccurate and lead to significantly reduced levels of safety for concrete structures in the event of fire. The inability to predict the occurrence of spalling has been a limiting factor in the development of robust models of the response of concrete structures to fire. As long as spalling remains unpredictable, fire engineering calculations and computerised simulations of fire resistance tests will not be reliable. By ignoring the effects of spalling, it is possible that current engineering models used to predict the fire resistance of concrete structural elements may produce unsafe results.

This possibility has been recognised by designers who, being unable to prevent spalling, has had to adopt measures to protect against its consequences.

6. TASK 5 SAFETY CRITERIA AND MEASURES

6.1 Objective of the Task

The main objective of the task has been: i) to define the structural safety features to be analysed and included in the WP5 holistic upgrading evaluation method; ii) Establish criteria for safer design and suitable cost efficiency; iii) Recommend cost efficient safer tunnel design.

The result of the task has been formulated in design and evaluation recommendation for cost efficient safer tunnel design. Particular effort has been given to describe the design process and the associated methods and boundary conditions.

6.2 Outline of the performed work

Task 4.5 has been carried out in the following activities: i) The structural safety features to be taken into account in the holistic upgrading design procedure were defined in collaboration with the task leader of task 5.3 in WP5: “Holistic evaluation and upgrading of existing tunnel safety”; ii) A clear definition of safety levels for existing configuration and system design was obtained by a collection and analysis of the current national regulations for tunnels regarding fire performance of structures; iii) Based on this, a method of system optimisation with an acceptable safety level was suggested. As part of the activity installation costs and maintenance of the design configuration were also investigated.

6.3 Engineering Comments and Advises

Tunnels vary with respect to structural concept, construction methodology as well as the natural condition and the type and amount of traffic. However, even taking this observation into account, it is remarkable how much the tunnel design guidelines vary from country to country.

The existing guidelines for design of tunnel structure against fire vary from guidelines which are prescriptive into the very detail and more or less performance based criteria. The criteria are given in terms of fire duration and specified fire curve or heat release rate. Some guidelines only give very general indications that the topic will have to be carefully assessed. The prescriptive design guidelines provide an evaluation of the safety of the tunnel which is relatively easy to use for the designer and for the controller. On the other hand the actual safety level underlying the prescriptive requirements is often very difficult to determine. It may be assumed that most guidelines are written on the basis of experience and administrative decisions rather than calibration to a certain safety level.

For the risk based approaches, i.e. the cost benefit analyses and to some extent the performance based approach some basic safety requirements may have to be defined and decided. This may involve for example maximum probability of failure and a quantification of the consequences. Particularly controversial is the quantification of the importance of fatalities.

For performance based design and natural fire curves a number of important parameters may need to be determined. The final design may be sensitive towards these parameters, and guidelines should be developed in order to have a harmonised basis for these parameters.

The prescribed fire curves which are required to be used for the documentation of the structural performance vary also significantly from guideline to guideline, from very short fires to fires with very high temperatures and long duration. The relation between the event scenario and the fire curve is in most cases difficult to detect.

Calculated documentation is required in all guidelines. In the least prescriptive guidelines a lot of freedom is left to the designer. For the designer of a tunnel there are a lot of steps between the indication of a fire scenario or a heat release rate to the practical design of concrete cross section and reinforcement. The analyses and the level of detail in each step of the performance based design should be specified in order to achieve a harmonised safety level by application of performance based design.

The evaluation of the technical solutions should take into account all the necessary information for determining the cost efficiency with regards to reduction of the risk of damage and other consequence in case of a fire. The disadvantage / costs for applying the technical solutions for tunnels in operation is in most cases the most serious consideration. The actual performance of the material or technical solution is another uncertainty which must be seriously considered. For this purpose tests can be included.

The choice between the technical solutions for upgrade of structural fire performance relies on a detailed analysis that is linked to each project. The optimisation of the system can be reached by a precise description of the expected properties. The optimisation must respect the available prescriptive guidelines and the requirements related to safety and structural reliability. Alternatively or in combination the design can be based on performance based approaches, risk based approach and the associated risk assessment and decision-making.

7. GENERAL REMARKS, INNOVATIVE RESULTS AND CONCLUSIONS

UPTUN aims at the development of cost-effective, sustainable and innovative upgrading methods for fire safety in existing tunnels. The WP 4 objective was to gain more detailed understanding of tunnel elements performance during a fire. The new knowledge can be used in the design and update of tunnels for prevention of heavy damages to the tunnel structures and functional equipment. Reduced fire damages have a beneficial economic effect in itself and also in terms of reduction of the non-operational time for a road or rail tunnel damaged by a fire accident. This has clearly a considerable socio-economic potential. Particular attention has so been given to the definition, production application and verification of new concrete materials and quick-economic in-situ damage assessment methods. Main conclusions are the following:

i) A rapid reinstatement of a functional tunnel can be obtained by the use of new quick damage level assessment methods and repair-recovery procedures, which have been defined and set up as part of the WP4 research work; ii) The new results of the work package included a check-up, comparison and validation of all design tools and methodologies used by the partners for design of tunnel structures and prediction of their behaviour during fire; iii) An experimental large scale fire testing was carried out on a suspended ceiling, which was identified as a critical structural component based on review of actual tunnel fires; iv) In addition semi-scale fire testing was carried out on selected functional equipment, which was identified based on a review of road and railway tunnels and fires in these tunnels. The tested equipment included: doors, signs and cables; v) Protecting doors are today certified according to the ISO curve. Commercially available doors are able to protect people for a reasonable time. The emergency doors passed the tests, no leakages were observed and the functional capacity remained; vi) The most important functionality of signs and indicators, the visibility, is highly affected by the production and distribution of smoke within the tunnel.

The visibility of each sample under investigation was lost after a few minutes if the smoke front was able to propagate to the installation points; vii) Predictions for the operability of the cables in different conditions should be made based on the specific data of the cables, tunnel geometry and fire conditions. The test carried out with different types of cables provided some useful indications about their operability; viii) As all of the tests for functional elements have been carried out in semi-scale the assessment of the results for full-scale situations is difficult. There are only estimations on temperature conditions possible that allow rough estimations on the operability of the devices; ix) In addition to the evident direct losses from a tunnel fire, closure of a tunnel due to fire can result in significant impact to mobility, to economy of the operator and to local economy and to society in general; x) After a fire it is important within a short time to understand the degree of damage and to establish an efficient repair with a minimum disturbance / disruption of the operation of the tunnel; xi) As part of UPTUN WP4 new innovative methods for damage detection and repair have been developed; xii) Significant progress has been made in connection with describing and understanding of the spalling phenomenon, prediction of spalling and measures to prevent spalling; xiii) Spalling can be addressed in existing tunnels by passive fire protection of the tunnel, which on the other hand of course involves significant costs; xiv) As part of UPTUN it has been achieved to release the theoretical “Users Manual” of the F.E.M. Code HITECOSP2. Structural design is a decision process which takes into account the structural safety; xv) In WP 4 the design process has been studied in detail particularly comparison of prescriptive guidelines and the discussion of possibilities for introduction of performance-based design and optimisation processes for design of tunnel systems have been part of the study.

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9. REFERENCES

1. F.Corsi et al., “Recommendations for safety components, instrumentation and systems for upgraded tunnels”, Deliverable D4.6, Doc. UPTUN 763 WP4, 23 March 2006, pp. 1-57.
2. G.A.Khoury and C.E.Majorana, “Effects of heat on concrete”, CISM Book no. 460, Taylor and Francis Eds., London, 2006.