Retrofitting of existing tunnels with concrete lining: a preliminary experimental investigation

Marinella Fossetti[a], Tullio Giuffrè[a], Giuseppe Macaluso[a], Alfio Francesco Siciliano[a], Giuseppe D'Arenzo[a], Rosario Davide Cottonaro[a]

[a] *Faculty of Engineering and Architecture, "Kore" University of Enna, Cittadella Universitaria - 94100 Enna, Italy*

Keywords: Retrofitting of tunnels; concrete lining; thin layer of high-performance mortar; experimental study.

ABSTRACT
Tunnels are a critical component of transportation infrastructure, but they are vulnerable to severe environmental conditions, accidental blast events as well as some structural damages coming from design or construction errors. Under these circumstances, they require repair and maintenance activities for which tunnels must be closed to traffic and the functionality of the transportation network is significantly impacted with increase of the costs of transport.
This paper provides an innovative retrofitting technique of the tunnels concrete lining. This technique involves the application of a thin layer of high-performance mortar on the damaged area of the existing lining. The main advantage of the analysed technique is that it doesn't need to apply directly loads in the foundation; moreover, it is possible to preserve a partial road circulation during the application of the strengthening with a consequent reduction of the economic losses. Since there are few experimental and theoretical studies on existing structures with on-side reinforcements, in this study a preliminary experimental investigation on eighteen 1:2 scale concrete lining elements was carried out under monotonic compressive load.
The aim of this preliminary experimental study is to investigate the performance equivalence between control lining elements (concrete elements without structural damages) and damaged concrete lining elements (thinner with respect to control elements due to an undesirable damage) one-sided strengthened. The experimental program includes studies on different thicknesses of strengthening and on different kinds of high-performance mortar. Results showed the reliability of the analysed repair technique.

1 INTRODUCTION

Many concrete tunnels were constructed to serve as important infrastructures as railway, subway, road transportation tunnels or water supply. As shown in Figure 1, concrete tunnels inevitably degrade for different reasons: material aging, aggressive condition and extreme loads etc. This is revealed in the form of concrete cracking, delamination and spalling, water leakage, and steel or reinforcement corrosion (Balaguer et al. 2014, Mashimo and Ishimura 2006, Mckibbins 2009).

As a public facilities, tunnels have to maintain satisfactory serviceability and the performance levels envisaged in the project, especially with regard to the seismic actions. In fact, any failure would affect its functionality, entailing a great damage to the economy and society. Consequently, it is important to ensure the appropriate maintenance for tunnels, in order to maintain the normal operation of facility with less cost.

This paper, first introduced tunnels damages in terms of concrete degradation and their causes, as well as the background for the efficient maintenance of these infrastructures. After, concrete tunnels repair is discussed, with respect to a new technique for tunnels rehabilitation using a thin layer of high-performance mortar on the damaged area of the existing concrete lining.

The aim is to combine protection and resistance properties of high-performance mortars and to improve significantly the structural performance in terms of durability and life-cycle costs of the rehabilitated concrete infrastructures (Brühwiler and Denarié 2008).

Several theoretical studies on two layers beams with partial interaction at the interface has been conducted from the pioneering work of Newmark et al. (1951) where only transversal load can be applied. On the basis of Newmark's hypotheses, static and dynamic analysis were performed in Girhammar and Gopu. (1993a) and Girhammar and Pan (1993b) respectively. Newmark's linear-elastic theory was extended to the axial loads by Wu et al. (2002) and shear coupled walls and beams strengthened by FRP sheets were analysed by Cosenza and Pecce (2001) by means of an analytical model similar to that of Newmark. Nevertheless, there are only a few experimental studies on one-sided strengthened elements.

Figure 1. Example of degraded concrete tunnels (repertoire image).

The aim of this preliminary experimental study is to investigate the performance equivalence between control lining elements (concrete elements without structural damages) and damaged concrete lining elements (thinner with respect to control elements due to an undesirable damage) one-sided strengthened.

A monotonic compressive load tests have been carried out for to verify the interfacial bonding between the existing concrete substrate and the repair material. It is well known that, the interfacial bonding between deteriorated concretes and new overlay repair materials is one of the most important factors for structural functionality, safety and durability (Momayez et al 2005, Tayeh et al. 2012).

The experimental program includes studies on different thicknesses of strengthening and on different kinds of high-performance mortar. Results showed the reliability of the analyzed repair technique.

2 TUNNELS DEGRADATION

Concrete tunnels unavoidably degrades over time, showing problems linked to leakage, deformation and concrete deterioration, due to initial defects, material aging, aggressive operation condition, extreme loads, and several other reasons. Tunnels degradation can cause aesthetic, serviceable, or structural problems. An interesting review of some of the principal degradation problems which could interest tunnels is discussed in Galan et al. (2019).

The main degradation phenomena that can affect the concrete lining are listed below.

Some chemical attacks like leaching, sintering and sulphate attack could interest tunnel lining due the interaction between the shotcrete and the interstitial solutions.

Leaching is a process where an aqueous solution undersaturated compared to cement phases seeps over and through a porous cementitious material, like shotcrete, leading to an increase of porosity, reduction of strength and disintegration of shotcrete. This process often emphasizes the beginning of other chemical attacks, such as sulphate attack and sintering.

As regards sintering, it is a process characterised by a precipitation of massive carbonate minerals on tunnel walls or in the tunnel drainage system. This comes out from the interaction between local percolating solutions, like groundwater and concrete layers. In order not to alter the function of the lining, precipitates have to be removed from a drainage system, preventing water pressure increase and blockages.

When it occurs an interaction between sulphate ions from local groundwater or drainage solutions and hydrated cement components, sulphate attack phenomenon takes place. There are some key factors which involve this kind of attack, like chemical composition and sulphate concentration in the water, permeability of the shotcrete and aluminate content in the cement. Moreover, environmental conditions play an important role as well.

Thaumasite sulphate attack is a special type but also the worst of sulphate attack which the cementitious material is transformed into a mushy product for, leading to a completely losing its binding/mechanical properties.

Other important problems concern exposure to freeze-thaw cycles and other durability related issues like the resistance to fire and high temperatures.

Freeze-thaw cycles such as de-icing salt exposure can seriously hit the durability of tunnel lining, mainly due to physical attack. Tunnel lining can be affected to freeze-thaw damage because of the exposure to water leaking from the rock and the low temperatures reached in winter season. Freezing water expansion in capillary pores could lead to internal damages because of increasing of the stresses from which cracks formation, reduction in Young modulus and surface scaling could happen.

Some of the factors concerning fire resistance of the tunnel lining are the degree of water saturation of the pores and their size, the thickness of the lining, mechanical loads, type of aggregates and several other reasons.

Even if tunnel lining is considered to be non-combustible and has good fire-resistance properties, in tunnelling structures, fire can lead to very unsafe situations. For this reason, steel fibres are often used to increase structural ductility and toughness of shotcrete layer, but also to create a microcracks network which helps releasing pore pressure, thus improving fire resistance. The latter technique used for shotcrete layer can be extended also to others mortars applied on the intrados of the tunnels.

In addition to the degradation phenomena just described, Wang (2018) schematically summarizes the problems concerning rebar and concrete, as shown in the Table 1.

Cracking phenomenon may happen as a result of material shrinkage, steel corrosion, extreme force and so on. The effect of a crack on aesthetic, serviceable or structural functions of a tunnel depends on its vehicle-traffic activity, location, dimension but also on the activity of the crack. If crack is active, it means that structural degradation of the tunnel occurs while, if it is a dormant one, the cause may be improper construction or material shrinkage.

Delamination process often occurs during concrete curing, but also due to the reaction of coarse aggregate or steel corrosion. After the delaminated surface layer completely detaches, concrete spalling occurs.

All these phenomena (cracking, delamination, spalling of concrete and corrosion of steel or reinforcements) can compromise the structural integrity of a tunnel and shorten its service life.

3 PRELIMINARY ISSUES ABOUT MAINTENANCE FOR TUNNELS REPAIRING OPERATIONS

Generally two typologies of maintenance techniques are used for the tunnels (Wang et al. 2016a, Wang 2018). The first one, where the maintenance activity is carried out after fails of the facility, typically called “corrective maintenance”. The second one, where the maintenance activity is regularly carried out in a defined periodic time, typically called “preventative maintenance”. Of course different advantages can be expected from the two techniques. For instance, the “corrective maintenance” techniques are more invasive and typically are used for transportation tunnels less than “preventative maintenance” techniques. However the tunnel degradation can depend on many aspects, such as materials and environmental conditions. For this reason the maintenance technique should be chosen considering all these boundary conditions.

The maintenance of the tunnels is typically performed going through several steps: periodic inspections, special inspections, performance evaluation and repairs or rehabilitations (see Figure 2 by JRB 2014). Periodic inspections are typically performed to visual level monitoring deterioration conditions of materials as corrosion, cracking and delamination/spalling. Special inspections are carried out when significant deteriorations are observed in the tunnels; in this case important structural rehabilitations are necessary, entailing high costs .

In other words, an efficient maintenance should be carried out to ensure that the tunnel is in good performance with no high costs.

Moreover, the maintenance of a tunnel involves the facility function, management policy, related technologies of inspection and structural rehabilitation (JRB, 2014; FHWA, 2015).

Table 1. Deterioration states described of rebar and concrete.

Deterioration State	Rebar	Concrete	
	Corrosion	Cracking	Delamination/Spalling
State I	Deterioration of the rebars begins with superficial corrosion in small areas.	Formation of thin cracks starts	The first delamination / spalling are occurred
State II	Corrosion progress starts to reduce the cross section area of the rebars with negligible structural effects.	Cracks occur along the steel reinforcement or in areas subjected to shear stress	The delamination / spalling are evident in limited areas
State III	Significant reduction of the rebars cross-section occur. The Bearing capacity of the structure could be profoundly compromised	The bearing capacity of the structure is compromised from cracks spread throughout the whole structure	Delamination / spalling occurs throughout the structure. Risk of an early collapse

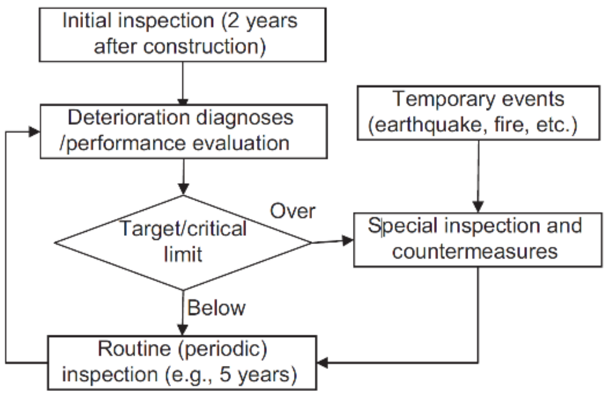

Figure 2. Chart of maintenance steps from JRB 2014.

As aforementioned, when the structural integrity of a tunnels has considerably declined, tunnels rehabilitation may be considered.

Many rehabilitation techniques were developed in recent years, as trenchless approaches, additional lining method for a large tunnel, and several others. (Najafi and Gokhale 2005, RTRI 2000).

All these techniques require that the circulation of vehicles is interrupted, thereby they entail an increase of the costs of transport.

With the proposed retrofitting technique, it is possible to preserve a partial road circulation during the application of the strengthening, with a consequent reduction of the economic losses.

4 EXPERIMENTAL PROGRAM

Experimental campaign consist of 18 concrete elements, 16 of which (reinforced elements) strengthened by means of a high performances mortar layer (reinforcement layer) on one side.

Three different mortars are used for the reinforcement layer:

- ©Planitop HPC is a ready-mixed free-flowing mortar made from two components. Component A (powder) is made of high-strength cement, selected aggregates and special additives while component B (HPC Fibres) consist of stiff steel fibres and it have to be mixed with component A with 6.5% by weight.
- ©Mapegrout Tissotropico is a ready-mixed powder mortar composed of high-strength cements, selected aggregates, special additives and synthetic fibres.
- ©Mapegrout Easy Flow GF is a pre-blended, one component thixotropic cementitious mortar, made from sulphate-resistant hydraulic binders, polyacrylonitrile synthetic fibres, inorganic fibres, organic corrosion inhibitors, special admixtures and selected aggregates.

Dimensions of the specimens derive from a preliminary finite element analysis of a representative sample of the lining subjected to compressive stresses. The specimens are made in 1:2 scale and have a total height of 1000 mm.

In order to verify the efficiency of the proposed retrofitting technique, two control specimens were made. Control specimens have a uniform cross-section along the longitudinal axis equal to 200x300 mm and are indicated by the letter “U”.

The specimens representative of the damaged concrete lining, have a cross-section equal to 125x300 mm.

The on-side reinforcement layer is made with two different thicknesses of 30 mm (corresponding to 6 cm in full scale) in and 40 mm (corresponding to 8 cm in full scale) respectively and, for each of them, an additional comparison has been performed between reinforcement layers with and without electro-welded mesh (ϕ6, 100x100 mm).

The on-side reinforcement was applied only on 800 mm since the ends of each specimen were appropriately confined in order to avoid the premature failure of the extremity during the application of the monotonic load.

On-side reinforcement layer is fixed to the existing concrete lining element, by means of four L-shaped ϕ6 shear connectors of 50 x 100 mm, arranged in a quincunx pattern. It is worth noting that the shear connectors arrangement has been defined after a preliminary elastic analysis performed by EF in order to assess the most suitable interface tractions.

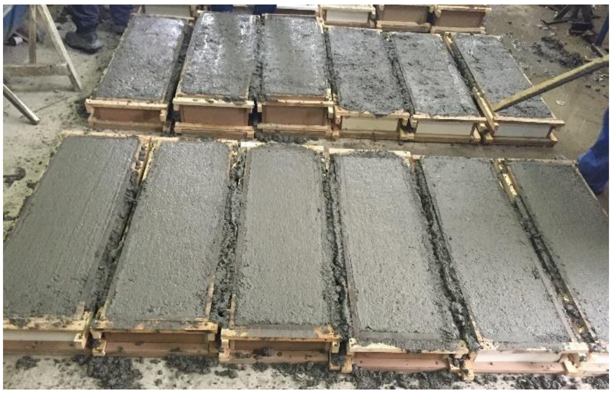

Figure 3. Casting of the specimens.

Furthermore, an additional local reinforcement, was installed at both ends of each column to avoid the failure in those parts earlier than failure of the global system.

Finally, in order to be able of making a meaningful comparison, for each kind of specimens, two elements with nominally identical characteristics were manufactured.

Table 3 summarizes the experimental program where the following symbols are used: the first three letters indicate the name of mortar used for the on-side reinforcement layer, the next number represents the thickness of the reinforcement layer, (*) indicates specimens without electro-welded mesh and the final letter (a or b) is used to distinguish specimens with identical characteristics.

The specimens were cast in formworks made of MDF (medium density fibreboard panels), placed horizontally and covered a plastic film to avoid the rapid interstitial water evaporation. On the same time, for the mechanical characterization of the mixture, several cubic samples of 150 mm and cylindrical specimens ϕ100 (high 200 mm) were casted (see Figure 3).

In order to install the on-side reinforcement, the following operations were carried out. Execution of the holes for the housing of the "L" shear connectors and subsequent removal of dust and loose particles from the inside of the holes by means of compressed air. Then, electro-welded wire mesh was placed by means of spacers. After that, shear connectors were installed with a chemical adhesive. The adhesive was applied by extruding, starting from the bottom, the resin inside the hole up to fill it and inserting "L" shear connectors into the hole by means of a rotary movement to remove the air, until the excess resin came out from the hole itself.

Welded net was fixed to the shear connectors by wire and then the spacers were removed after the chemical adhesive hardened. In Figure 4 are shown the specimens with and without electro-welded mesh.

Finally, formworks needed for casting of the on-side reinforcement were installed and surface were cleaned by means of high pressure water to eliminate dust and incoherent parts. Figure 5 shows photos of the three types of high performance mortar used for on-side reinforcement.

It is important to highlight that, in this preliminary experimental investigation, for safety, the preparation of the support surface was not performed by scarification.

In order to avoid the rapid evaporation of the mixing water, all the strengthened elements were constantly humidified, covered with polyethylene sheets and left to curing in a suitable environment.

Figure 4. Installation of the electro-welded net and shear connectors.

The tests were carried out at the Structure Laboratory of the LEDA Research Centre (Fossetti et al. 2017). Compression tests on the elements were performed using the test set-up shown in Figure 6. It is essentially made up of a 2000 kN Rexroth actuator with servo-hydraulic control operating both force and displacement control, from a steel contrast frame, from a hydraulic control unit, from a control system, produced by the manufacturer TRIO Sistemi, equipped with "RT3" software and an acquisition system consisting of a series of external transducers.

(a) (b) (c)

Figure 5. Application of high performance mortar: (a) ©Planitop HPC; (b) ©Mapegrout Tissotropico; (c) ©Mapegrout Easy Flow GF.

In particular, the RT3 controller consists of an embedded system managed by a software application, developed in a Labview environment that operates in Real Time. The electronic modules are integrated in the RT3 system which allows the conditioning of the transducers, the piloting of the servo valves and the management of the hydraulic equipment based on the specific characteristics of the final application. Therefore, the RT3 control program allows the complete management of the test equipment, from the setting of the optimal configuration parameters, to the execution of the tests and to the measurement and recording of the acquired data that can be subsequently exported.

The transmission of the signals coming from the measurement sensors to the central unit is digital. In this way it is possible to guarantee the total absence of disturbances in data transmission and therefore the absence of errors in the measurement of the experimentally detected quantities.

5 EXPERIMENTAL RESULTS

1.1 Mechanical characterization of materials

Samples packaged to characterize the concrete mixture and mortars were cured under the same conditions of the specimens. In accordance with UNI-EN 12390/1-3, concrete compression resistance curve as a function of curing time has been made and the average value of the maximum concrete compression stresses after 28 days of curing is 42.41 N / mm^2.

Mechanical characteristics of the high performance mortars were determined by means of centred compression tests on 150 mm cubic side specimens and with bending tests on prismatic specimens 160 x 40 x 40 mm. The average of the results obtained after 28 days of curing were found to be consistent with the indications provided by the manufacturer as indicated in Table 2.

Table 2. Main characteristics of the high performance mortars at 28 days of curing.

	©Planitop HPC	©Mapegrout Tissotropico	©Mapegrout Easy Flow GF
Compressive strength (MPa)	130	60	60
Flexural strength (MPa)	32	8.5	8
Elastic modulus (GPa)	37	26	27

1.2 Compression test on reinforced and control elements

The tests on the elements were conducted using the set-up described in Figure 6 with displacement control. Vertical load was applied directly on the existing concrete lining end by means of two steel plates with a thickness of 50 mm in order to guarantee the uniform distribution of the applied load. Furthermore, in order to avoid the premature collapse of the not reinforced elements ends, they were confined with steel stirrups placed under tension with a system of screws and nuts.

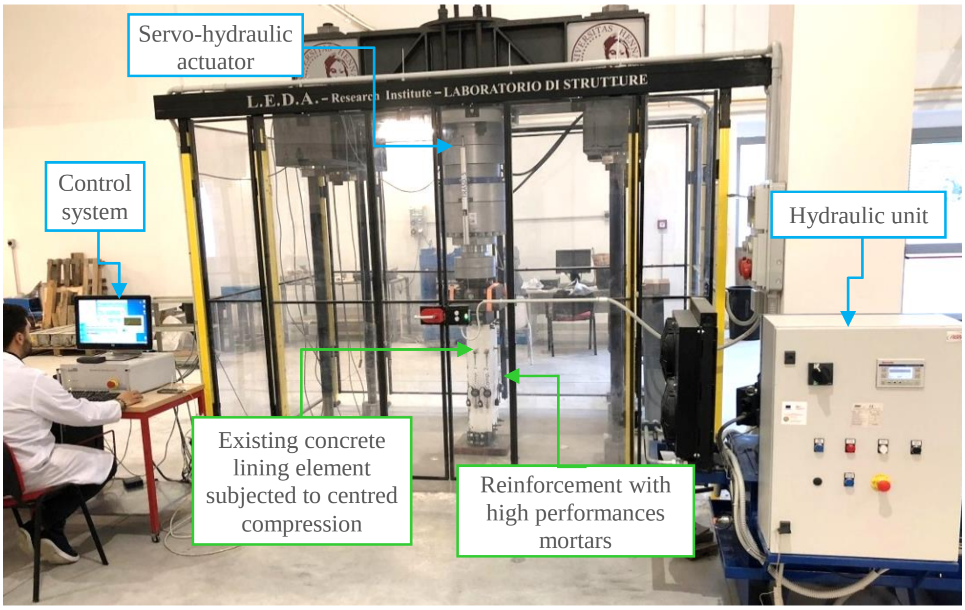

Figure 6. Experimental set-up.

However, there is not contact between the latter and the reinforcement layer so that applied load at the existing concrete lining is transferred to the reinforcement layer only through the tangential tensions developed at the interface.

All tests were carried out with the rate of 0.01 mm/s. During the test the reactive force and the vertical displacement of the elements ends were recorded by the machine's RT3 control system.

In all the specimens, near the peak load, due to the lateral expansion of the concrete, sub-vertical cracks occur, followed by a typical noise linked to the cracking of the existing concrete lining. The failure of the existing concrete lining leads to activation of a collapse mechanism of the system and the consequent deboning of the reinforcement layer. Once the failure occurs, no significant damages are detected on the reinforcement layer. From this remark it is possible to state that the interface had an adequate mechanical behaviour to allow the failure of the global system (see some details in Figure 7).

All elements have a brittle behaviour although they showed an initial different behaviour with respect to the type of mortar used to make the reinforcement. In particular, specimens strengthened with the mortar © Planitop HPC have greater initial stiffness than those made with © Mapegrout Tissotropico and © Mapegrout Easy Flow GF probably because the © Planitop HPC mortar has elastic modulus and resistance of the greater the other mortars. For the same reason, in the elements reinforced with ©Planitop HPC a greater damage to the concrete existing concrete lining is observed and a slower detachment of the reinforcement layer, presumably thanks to the better mechanical characteristics of the mortar.

Table 3 shows the maximum load reached (F_{max}) for each column, the average value for each specimen type (F_M) and the maximum load increment evaluated with respect to the average value of the control specimens. The results obtained for the specimens TISS_30_b and TISS_40_b are not reported because they showed an anomalous behaviour probably due to a wrong manufacturing.

From the results summarized in Table 2, it can be stated that a reinforcement layer made with high performance mortars greatly improve the behaviour of the concrete elements. The most evident effect is constituted by a significant increase in the bearing capacity with respect to the control elements. In fact, a reinforcement layer of 30 or 40 mm tick, placed on one side of the concrete elements, leads to an increase of the failure load against a reduction of the existing concrete lining cross section of about 38%. In particular, Table 3 shows that failure load of the strengthened elements is increased of about 14.96% for the ©Planitop HPC mortar, of about 8.61% for the © Mapegrout Thixotropic mortar and of about 5.98% for the ©Mapegrout Easy Flow GF. Furthermore, it can be observe that elements strengthened by means of layer 30 mm thick show failure load greater than that of the elements reinforced with the same mortar but with thicknness of 40 mm.

This result can be explained observing that increasing the reinforcement layer thickness involves a greater displacement of the cross-section centroid of the element to which an increase of the bending state could be associated and consequently worsening the safety conditions.

(a) (b) (c)

Figure 7. Details of failure mode for one-sided strengthened elements: (a) Strengthened with ©Planitop HPC; (b) Strengthened with ©Mapegrout Tissotropico; (d) Strengthened with ©Mapegrout Easy Flow GF.

Table 3. Maximum compressive load obtained from centred compression tests.

SAMPLE	Maximum load recorded		Maximum load increase	Reinforcement thickness [mm]	Name of the mortar
	F_{max} [kN]	F_M [kN]			
U_1	1249.43	1195.84	---	---	---
U_2	1142.25				
HPC_30_a	1324.83	1324.83	10.79%	30	© Planitop HPC
HPC_40_a	1182.31	1305.79	9.19%	40	© Planitop HPC
HPC_40_b	1429.27			40	© Planitop HPC
HPC_30*_a	1233.59	1426.43	19.28%	30	© Planitop HPC
HPC_30*_b	1619.27			30	© Planitop HPC
HPC_40*_a	1152.996	1416.90	18.49%	40	© Planitop HPC
HPC_40*_b	1680.79			40	© Planitop HPC
TISS_30_a	1296.41	1296.41	8.41%	30	© Mapegrout Tissotropico
TISS_40_a	1301.25	1301.25	8.41%	40	©Mapegrout Tissotropico
FGF_30_a	1122.09	1302.15	8.89%	30	© Mapegrout Easy Flow GF
FGF_30_b	1482.21			30	© Mapegrout Easy Flow GF
FGF_40_a	1142.76	1232.66	3.08%	40	© Mapegrout Easy Flow GF
FGF_40_b	1322.56			40	© Mapegrout Easy Flow GF

Finally, we can also observe that elements without welded net have a greater bearing capacity. Probably, the greater axial deformability of the reinforced layer without welded net allows make the most of interface behaviour because there are less relative displacements. However, this conclusion needs further experimental investigations in order to obtain general validity.

6 CONCLUSIONS

In this paper a new reinforcement system for concrete tunnels has been experimentally studied on 1:2 elements.

The technique involves the application of a high performance mortar layer on the tunnel intrados. The layer has been fixed to the support by means of a shear connectors and it can be reinforced by electro-welded net. The system has been validated through an experimental campaign consisting of 18 concrete elements, 16 of which strengthened by means of a high performances mortar layer applied on one side. The existing concrete lining cross-section dimensions of the reinforced elements are smaller than cross-section of the concrete elements (control specimens) of about 38%. It worth noting that the latter reduction can derive from a generic degradation condition (severe environmental conditions, accidental blast events, construction errors, etc.). Two reinforcement layer thickness of 30 and 40 mm are used but it should be noticed that whole cross-section dimension of the reinforced elements are less than those of the control specimens. The reinforced layers are made with three different high performance mortars called ©Planitop HPC, ©Mapegrout Tissotropico and © Mapegrout Easy Flow GF.

Experimental campaign is conducted comparing compressive behaviour of the reinforced elements and control specimens from which can be concluded that:

- The proposed reinforcement technique allows to restore the performance equivalence between concrete elements without structural damages and damaged concrete elements (thinner with respect to control elements due to an undesirable damage), strengthened on one-sided.
- In spite of cross-section of the existing concrete lining of the strengthened elements were reduced by about 38%, the bearing capacity of the control specimens was restored and an average increase of the maximum load of about 11.22% was recorded.
- The interface behaviour was generally good and strong enough. In particular, interfacial failure occurred after the substrate experiencing some degree of damages.
- The reinforced technique allows to restore the original behaviour of the control element by means of a thin reinforcement layer of high

performance mortar applied on one side but the thickness of the latter should be designed ad-hoc. In fact, although further studies are needed, we observed that elements strengthened by means of the layer 30 mm thick show failure load greater than those of the elements reinforced with the same mortar but with thickness of 40mm due the cross-section centroid displacement.

- The stiffness of the reinforcement layer should not be much bigger than that of the existing concrete lining.

In spite of further investigations should be addressed to generalize the results obtained, this paper gives a preliminary experimentally contribution on a new structural reinforcement technique. It finds a performance equivalence between elements with different core thicknesses without directly apply loads in the foundation.

Finally, this retrofitting technique allows to preserve a partial road circulation during its application with a consequent reduction of the economic losses due to increase of the transport costs.

ACKNOWLEDGEMENTS

The company MAPEI S.p.A. is gratefully acknowledged for financial support to the experimental campaign presented in this article.

REFERENCES

Asakura, T., Kojima, Y. (2003). Tunnel maintenance in Japan. Tunnel. *Underground Space Technol*. 18 (2), 161-169.

Balaguer C., Montero R., Victores J.G., Martínez S., Jardón A. (2014). Towards Fully Automated Tunnel Inspection: A Survey and Future Trends. ISARC 2014, 31st Internat. Symposium on Automation and Robotics in Construction and Mining. July 9-11, 2014 Sydney, Australia.

Brühwiler E., Denarié, E. (2008). Rehabilitation of concrete structures using Ultra-High Performance Fibre Reinforced Concrete. UHPC-2008: The Second International Symposium on Ultra High Performance Concrete. March 5-7, 2008, Kassel, Germany.

Cosenza E., Pecce M. (2001). Shear and Normal Stresses Interaction in Coupled Structural Systems. *Journal of Structural Engineering*, 127(1):84-88.

Federal Highway Administration (FHWA), 2015. National Tunnel Inspection Standards (NTIS). Federal Highway Administration.

Fossetti M, Lo Iacono F, Minafò G, Navarra G, Tesoriere G. (2017). A new large-scale laboratory: the LEDA Research Centre (Laboratory of Earthquake engineering and Dynamic Analysis). Proc. of Intern. Conf. 7aese, Pavia, 6-8 Sept. Publisher: *EUCENTRE Foundation*.

Galan I, Baldermann A, Kusterle W, Dietzela M, Mittermayr F., (2019). Durability of shotcrete for underground support– Review and update. *Construction and Building Materials* 202, 465–493.

Girhammar U. A. and. Gopu V. K. A (1993a). Composite Beam-Columns with Interlayer Slip-Exact Analysis. *Journal of Structural Engineering*, 119(4):1265-1282.

Girhammar U. A. and. Pan D. (1993b). Dynamic analysis of composite members with interlayer slip. International *Journal of Solids and Structures*, 30(6):797-823.

Japan Road Bureau - JRB, (2014). Road tunnel routine inspection manual. Tokyo, Japan Road Bureau of Ministry of Land, Infrastructure, Transport and Tourism.

Mckibbins L., Elmer R., Roberts K. Tunnells inspection assessment and maintenance. CIRIA Report C671, London 2009.

Mashimo, H., Ishimura, T. (2006). State of the art and future prospect of maintenance and operation of road tunnel. ISARC 2006 - 23th International Symposium on Automation and Robotics in Construction ISARC. October 3-5, 2006 Tokyo, Japan.

Momayez A, Ehsani MR, Ramezanianpour AA, Rajaie H. (2005). Comparison of methods for evaluating bond strength between concrete substrate and repair materials. *Cement Concrete Res*, 35 (4), 748–57.

Najafi, M., Gokhale, S., (2005). Trenchless Technology: Pipeline and Utility Design, Construction, and Renewal. McGraw Hill Professional.

Newmark M.N., Siess C.P., Viest I.M. (1951). Tests and analysis of composite beams with incomplete interaction. In *Proceedings of the Society for Experimental Stress Analysis*. 9 (1), 75-92.

Railway Technical Research Institute - RTRI (2000). Design Manual of countermeasure to deteriorated tunnel. Railway Technical Research.

Tayeh B.A., Bakar BH.A., Johari MA. M., Voo Y.L. (2012). Mechanical and permeability properties of the interface between normal concrete substrate and ultra high performance fiber concrete overlay. *Construction and Building Materials* 36, 538–548.

UNI-EN 12390/1-3: (2003). Testing hardened concrete. Compressive strength of test specimens.

Wang J., Koizumi A., Tanaka H. (2016a). Framework for maintenance management of shield tunnel using structural performance and life cycle cost as indicators. *Structur. Infrastruct. Eng.* 13 (1), 44-54.

Wang JH., (2018). Lifecycle cost and performance analysis for repair of concrete tunnels. *Eco-Efficient Repair and Rehabilitation of Concrete Infrastructures. Woodhead Publishing Series in Civil and Structural Engineering*. Pp.637-672. Nippon Koei Co., Ltd, Tsukuba, Ibaraki, Japan.

Wu Y. F., Oehlers D. J., and Grith M. C. (2002). Partial-interaction analysis of composite beam/column members. *Mechanics of Structures and Machines*, 30(3):309332.