DURABILITY INVESTIGATION OF CALVARIA BRIDGE AND ELECTROCHEMICAL REALKALINISATION AS A PREVENTIVE MEASURE

Meda NEDELCU[1], *Camelia NEGRUTIU*[2],
[1] Engineer, M.Sc., meduta@gmail.com
[2] Lecturer, Ph.D., Technical University of Cluj-Napoca, Faculty of Civil Engineering, Department of Structures, camelia.negrutiu@dst.utcluj.ro

ABSTRACT

The purpose of this study is to investigate the performance of reinforced concrete structures during their service life. Environmental attacks, such as the atmospheric carbon dioxide and the deicing chloride salts ingression, may seriously affect both the concrete section and the embedded reinforcement and may lead to failure, if immediate measures are not taken. Therefore, a case study of a real structure, the Calvaria Bridge, an intense traffic node in Cluj-Napoca, Romania, was performed, with emphasis on the effects of durability aspects on the structural performance of the elements, namely in terms of deflection. A modern repair method, electrochemical realkalinisation, was also tested in the laboratory, in order to provide a proper intervention solution to the structure, for the concrete elements affected by the ingress of carbon dioxide and thus, by carbonation.

Keywords: damage; carbonation; chlorides; bridge; realkalinisation

REZUMAT

Scopul acestui studiu a constat în investigarea comportării structurilor de beton armat în perioada de serviciu. Agresivitatea mediului, cum ar fi pătrunderea dioxidului de carbon din atmosferă sau a clorurilor provenite din sărurile de dezgheţare, poate afecta atât secţiunea de beton cât şi armătura înglobată şi poate conduce la cedare, dacă nu se iau măsuri imediate. De aceea, s-a efectuat un studiu de caz al unei structuri reale, Podul Calvaria, un nod de trafic intens din Cluj-Napoca, Romania, cu detalierea efectelor aspectelor de durabilitate asupra comportării structurale a elementelor, şi anume asupra deformaţiilor. De asemenea, o metodă modernă de reparare, realcalinizarea electrochimică, a fost testată în laborator pentru a putea furniza o soluţie corectă de intervenţie asupra unei structuri, pentru elementele de beton armat afectate de pătrunderea dioxidului de carbon şi deci, de carbonatare.

Cuvinte cheie: degradări; carbonatare; cloruri; pod; realcalinizare

1. INTRODUCTION

The durability of reinforced concrete structures is strongly affected by the aggressive action of the environment. The durability of structures became a design criteria rather recently, as it reflects life in normal parameters of the building, such as ensuring functionality for the whole service period with minimal maintenance costs and zero repair costs. Over the years, a number of researchers from different fields sought means to protect the concrete elements from the action of physical and chemical processes such as carbonation, chloride attack, effects of freezing and thawing and sulfate attack.

As Vrabie and Băetu state, a high performance of structures should be reached, as this brings a surplus of quality of life for people who live, work in that structure or use the existing infrastructures [16].

One of the directions that define the economic research and initiative for building in a sustainable fashion, refers to how climate affects structures, especially the environmental temperature, the relative humidity and the chemical composition of the air [12, 13]. Under these conditions, a traffic increase, as occurring in most cases for highway and road constructions, thus a change in the design assumptions, can only exacerbate the problem [13].

Among the key factors that lead to the advanced deterioration of bridges [13] is carbonation, a chemical process that reduces the pH of concrete under the value of 9, thus favoring reinforcement corrosion. The carbon dioxide from external sources, CO_2, penetrates the concrete by diffusion and reacts with alkalis in the concrete structure; the reaction is described by the following chemical equation:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad (14)$$

Carbonation has a beneficial effect on the concrete itself, without reinforcement, reducing the overall porosity, together with a slight increase on strength [4]. A healthy, un-carbonated reinforced concrete maintains a high level of alkalinity, which protects the embedded reinforcement from corrosion. The steel reinforcement acts as a cathode when in passive state, but, when the level of pH of concrete decreases, the protection of the passive layer deteriorates and the reinforcement starts to act as an anode and begins to corrode [10].

The carbonation rate depends on the concentration of the external source of CO_2, the concrete alkalinity and permeability and the relative humidity, which is most deleterious at 60-70% (4). Furthermore, a low water/cement (w/c) ratio reduces the depth of carbonation or significantly influences the carbonation phenomenon [1, 2, 7].

Modern intervention methods for restoring structural safety involve, among others, re-establishing the concrete alkalinity and preventing the reinforcement corrosion through electrochemical realkalinisation (ER), which is a non-destructive method that uses electric current, anolytes and anodes.

However, if the carbonation process has passed the concrete cover, reaching the reinforcement, more complex repair measures must be taken, before a significant loss of steel by corrosion, and thus, a possible failure of the affected element, occurs.

The effectiveness of ER depends on the electrical charge applied to the steel reinforcement, usually for 1-2 weeks between 0.8 and 2.0 A/m^2 [1, 11]. The rather short treatment period is quite preferable to other techniques, due to easiness in application and low costs [8].

The electrolytes most commonly used in ER, which facilitate ion conductivity between the anode and cathode are K_2CO_3 or Na_2CO_3. Also, calcium hydroxide, potassium hydroxide [1], lithium hydroxide or plain water [5] can be used. However, these substances may induce certain supplementary problems in the concrete, such as the alkali-silicate reaction (ASR), with lower risk of occurring for the use of K_2CO_3, as compared to Na_2CO_3 [8], when using aggregates susceptible to this reaction. On the other hand, M.G. Grantham states that also the introduction of potassium ions in the electrolyte using K_2CO_3 can lead to the risk of developing ASR [9]. Therefore, further research should be conducted to assess the exact risk of developing ASR, when using certain electrolytes in ER. The most frequently used concentration of the anolyte solution is 1M of K_2CO_3 or Na_2CO_3 or other electrolyte [5, 9, 11].

As anode, steel or titanium mesh [4] or mortars with a high content of graphite [8] have been used.

According to F. Gonzales et al.[8], even if ER is performed on a partially carbonated concrete, with the carbonated depth larger than the reinforcement concrete cover and the level of alkalinity almost fully restored, it is still not sufficient to guarantee the re-passivation of the steel reinforcement. In fact, some tests revealed that, after finishing the ER, after a short time of exposure, the steel began to de-passivate again [8]. Therefore, the method is viable only for carbonated concrete depths smaller than the concrete cover, with non-affected reinforcement.

2. SCOPE OF THE STUDY

The purpose of this study is to investigate the performance of a real structure affected by the environment and to propose the appropriate solution for repair and extension of the service life. The Calvaria Bridge was selected because it shows advanced degradation from the action of aggressive physical and chemical processes that ultimately, with no adequate interventions, would lead to failure. The damage of this structure occurred because of poor design and construction and the lack of maintenance required during the service period. Therefore, a thorough visual inspection was performed and previous repair methods were assessed. A theoretical evaluation of a possible failure by assessing deformations in order to exclude immediate danger was carried out and a possible repair method, such as the electrochemical realkalinisation (ER) for inversing the carbonation of the concrete was studied and tested in controlled laboratory conditions. Further steps for continuing the study are also in plan: developing a technical proposal to the City Council of Cluj-Napoca and retrieving all the necessary approvals for an in situ testing of the ER.

3. RESEARCH PROGRAM

3.1. Description of Calvaria Bridge

The Calvaria Bridge is located on the artery entry in Cluj-Napoca from Oradea. The bridge is part of a road junction that provides the main traffic flow direction Oradea - Cluj-Napoca center and crosses an intersection in the central area (Fig. 1).

Fig. 1. Calvaria Bridge

According to a technical assessment performed by the City Council of Cluj-Napoca [6], the construction was completed and the bridge was delivered to public use in 1987. Unfortunately, to the author's knowledge, the assessment is the only document that exists in the municipal archives of all documentation on the design and construction of Calvaria Bridge. The structure has two main constituents: the bridge, with seven spans: 12 m + 5 x 23 m + 12 m, of a total length of 139 m, and the access ramps, fitted with retaining walls at every 99.30 m, with a total length of 337.60 m. The roadway width is 14 m, corresponding to four lanes - two on each side (3.5 m), and two sidewalks, each 1.65 m wide [6].

Furthermore, each clear span of 12 m is supported by 13 hollow-core, one way slabs, 520 mm-high, while each clear span of 23 m is supported by 16 hollow-core, one way slabs, 720 mm-high (Fig. 2). The reinforced concrete piles are spaced at 9.5 m and are composed of four different columns with a cross-section of 700 x 1000 mm, raked up at top with a wide reinforced concrete beam. All elements of the infrastructure have direct foundations.

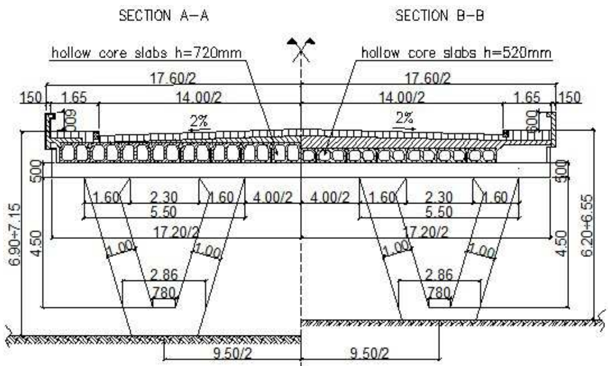

Fig. 2. Cross sections of the bridge [6]

3.2. Visual inspection of the Calvaria Bridge

Large cracks can be observed in all structural elements. For example, shear force inclined, all-through cracks are present on the retaining walls (Fig. 3). These cracks have favored infiltration of surface waters, improperly evacuated from the traffic lanes upwards and also sprayed from downwards, which carried concentrated aggressive chemicals found in fuel leaks from heavy traffic and deicing salts from winter maintenance. The red color abundant in the cracks is a sign of reinforcement corrosion products, as reached by the chemicals. The cracks also allowed CO_2 to enter much easier, and so that the concrete layer was also carbonated.

Other deteriorations are shown in Figure 4, at the joint between the retaining wall and the access path.

Fig. 3. Crack in the retaining walls

Fig. 4. Degradation of the retaining walls

The map-shaped cracking pattern may be caused by low temperatures in the winter, the so called phenomenon of d-cracking or from the alkali-aggregate reaction. The exposure of the aggregates due to freezing can be seen at the bottom of the retaining wall. All these defects intensify the aggressiveness of the upcoming attacks and reduce the overall capacity of the elements.

Over the abutments, Figure 5, a wide crack was observed, as a result of additional charges, thus stresses, due to the traffic increase over time. However, the crack is filled with moss and dark green and red products. Once again, the constant infiltration of waters will produce concrete disintegration, but this effect is not an immediate threat, due to the over sizing of the element.

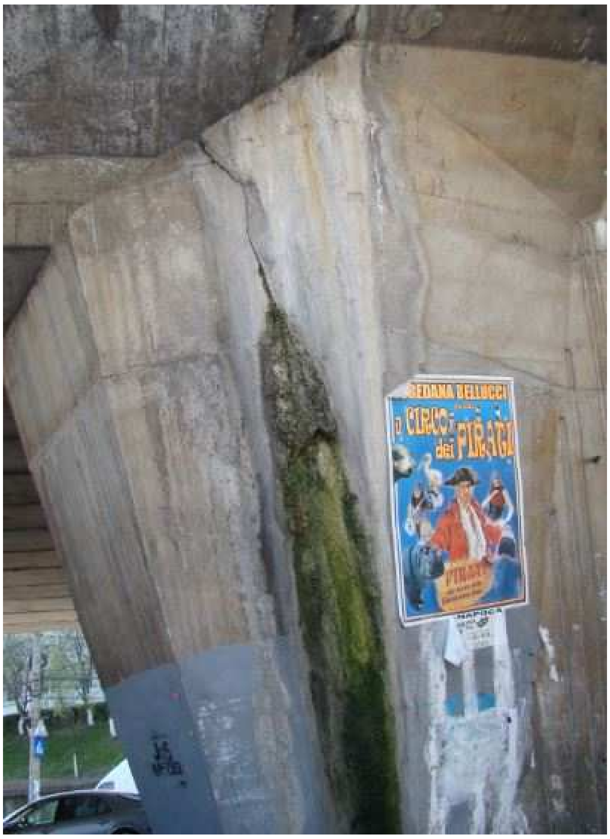

Fig. 5. Crack in the abutments

The main longitudinal elements are made of prestressed concrete and are presented in Figure 6. Although current design standards, such as SR EN 1992-1-1:2004, more specifically, the Eurocode 2, recommend a concrete cover as a function of the exposure class, in 1987, the Romanian standards would only take into consideration how to ensure the bonding between the reinforcement and the concrete in evaluating the concrete cover. However, for prestressed concrete elements, the imposed cover is close to current exposure class-based calculations and therefore, this is not a sufficient reason for assuming deterioration. The quality of the concrete cover, the actual composition of the concrete, with low quantities of cement and quite high porosity is more likely to be the cause of deterioration. The corrosion in the stirrup, which can lead to a brittle shear failure, is so advanced that stirrup position is easily observed from the distance. Most water seepage is observed on external slabs and this is because the tilting of the roadway is from the shaft to the outside (sidewalk) and rainwater collection is poorly performed in this area.

Fig. 6. Marginal deteriorated beams

The white stains on the slab bottoms are actually deposits of salts formed due to the permanent water infiltrations.

In Figure 7, a transversal simply supported beam in advanced state of corrosion is presented. Again, the shear capacity of the beam is at risk, with all the stirrups in corrosion, with reduced cross sections, especially where the shear-force is significant. At midspan, where bending stresses are important, the transverse reinforcement acts as a "sacrificial" element for the longitudinal reinforcement, allowing more time for the corrosion to reach the longitudinal bars.

Fig. 7. Corrosion of reinforcement

Due to carbonation and chloride attack, the expansive nature of the corrosion products, resulted in cover spalling when the tensile strength of concrete was exceeded. The presence of the sulfate attack is observed in these elements in Figure 8 by the appearance of white icicles.

Fig. 8. White icicles.

These formations result from the washing by the infiltrating water of the calcium carbonate present in the concrete composition.

The most important problem that appears with the occurrence of these formations is that the concrete becomes more porous, and thus, more susceptible to CO_2 attack, which induces the carbonation of concrete.

The columns have been recently consolidated. Therefore, visual defects, if existent, were hidden. However, a patch repair of a carbonated concrete, without the re-passivation of the embedded reinforcement is known only to worsen the rate of the corrosion and the exfoliation. Because the bridge pillars were subjected to the same aggressive environment which affected the rest of the structure, it is safe to assume that these elements were also damaged, consistent with Ball and Whitmore's halo effect theory [3]. The statement is confirmed by the exfoliation of the concrete cover in a consolidated pillar zone, as seen in Figure 9.

Fig. 9. Exfoliation of the new concrete layer

3.3. Influence of the reinforcement section loss on the vertical deformations

The durability analysis is complicated and time consuming and it usually involves combined knowledge in diverse fields such as Civil Engineering, Physics and Statistics, which makes it quite difficult to use. In already damaged structures, the problem might have an easier solution, by estimating, using non-destructive testing methods, the remaining constituents of a reinforced concrete structure: the actual cross-section, the remaining reinforcement and so forth. With the new set of data, a static analysis can be performed with direct and immediate results, to obtain the residual flexural or shear capacity. Other methods involve a service life analysis of the deflections.

For the Calvaria Bridge, the main clear span of 23 m was analyzed in terms of vertical deformations. Two scenarios were assessed: in the first one, the structure is intact, at full capacity. The loads correspond to Class E, in which a V80 convoy is applied at minimum 80 m throughout the length of the bridge [15] and it consists of a string of unlimited special vehicles on wheels, each vehicle having a weight of 800 kN (80 ton mass).

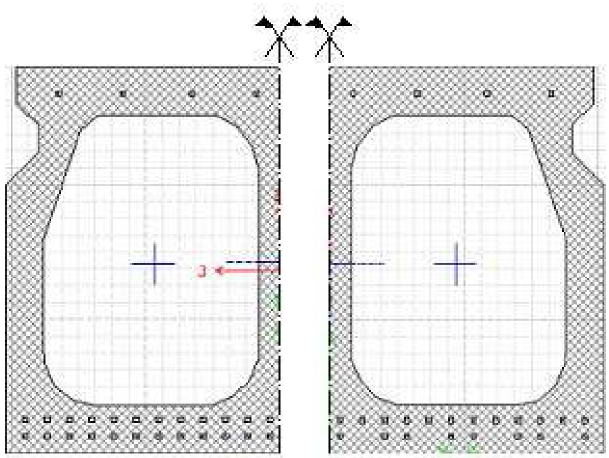

Fig. 10. Cross sections used in static analysis. Left section – scenario 1, right section – scenario 2

In the second scenario, the deteriorations were taken into account by removing the original number of strands in the assumption that they were reduced by corrosion and no longer carrying loads. The cross sections used in the analysis, for each of the two cases, are presented in Figure 10. The results show that a loss of 16.66% of the active reinforcement led to a vertical deformation at midspan increased by 1.30 mm in the second scenario, as compared to the first one, which means approximately 2.40%. The beam has sufficient rigidity due to the cross-sectional shape which brings a high inertial moment and which was not modified in either the scenarios, but could lead to important changes in the service life performance of the structure.

3.4. Electrochemical realkalinisation

One of the repair methods in structures affected by the carbonation, in which reinforcement is not yet corroded, is the electrochemical realkalinisation ER. Testing the process in controlled laboratory conditions is intended for assessing the influence of the concrete composition on the results of the ER repair method.

3.4.1. Concrete specimens

Two concrete compositions were tested: M1 with water/cement (w/c) ratio of 0.60 and M2 with water/cement (w/c) ratio of 0.40. The details of the compositions are presented in Table 1 and Table 2. For each composition a series of 100x100x300 mm prisms were cast, each with an embedded reinforcement, 8 mm-diameter BSt500S, as shown in Figure 11. The reinforcement was partially covered with silicone coating, as expressed by the shaded area.

Table 1. *Concrete mix M1 - w/c=0.60*

Materials	Quantity / m^3
Portland Cement CEM I 52.5R	300 kg
Granite Aggregates 0-4 mm	1061.01 kg
Granite Aggregates 4-8 mm	378.932 kg
Granite Aggregates 8-16 mm	454.718 kg
Water	180 liters
High range water reducer Sika Viscodur	1.5 liters

Table 2. *Concrete mix M2 - W/C=0.40*

Materials	Quantity / m^3
Portland Cement CEM I 52.5R	450 kg
Granite Aggregates 0-4 mm	987.848 kg
Granite Aggregates 4-8 mm	352.803 kg
Granite Aggregates 8-16 mm	423.364 kg
Water	180 kg
High range water reducer Sika Viscodur	2.25 liters

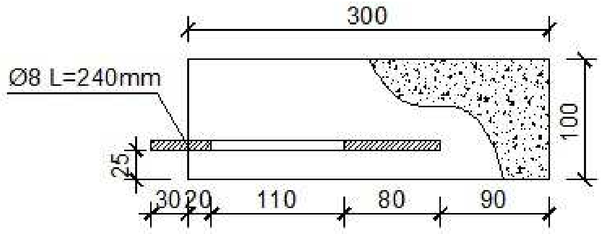

Fig. 11. Prism sketch (all dimensions are in mm)

3.4.2. The carbonation depth

After casting, the concrete prisms were demoulded after 24 h, cured for 4 days in water and then placed in the natural environment for 63 days in order to obtain a carbonated layer less that 25 mm-thick, which is the size of the concrete cover. The specimens were then split and the carbonated depth was evaluated by spraying the concrete surface with a 1% Phenolphthalein solution, as shown in Figure 12.

Fig. 12. Split samples

Although granite aggregates are usually important for concrete strength development, especially for high strength concrete, in this case, the resulting concrete samples were visibly porous as the aggregates lacked a high percentage of fine particles. Thus, deleterious gases, such as carbon dioxide are able to easily penetrate a weak, porous structure, which otherwise would not be prone for attack. For concrete samples with 0.40 w/c ratio, the carbonation depth was below 2 mm, whereas for the 0.60 w/c ratio, the average depth measured on the side where the realkalinisation was later applied was 10 mm, as shown in Figure 13.

Fig. 13. Measuring the depth of carbonation

The carbonation depth was lower for samples with w/c = 0.40, as the resulting structure was denser compared to that of the samples with higher w/c ratio. Therefore, it is obvious that a low w/c ratio has a significant influence in the development of compressive strength, the increased density of the concrete matrix and thus the decrease in carbonation depth. This observation is also confirmed by Aguirre and Mejía [1] and by Al-Khaiat et al. [2].

3.4.3. The electrochemical realkalinization procedure

The set up test for RE is presented in Figure 14. An 8 mm-diameter mesh of ribbed steel, type Bst500S, acted as anode, while the embedded reinforcement acted as cathode. A textile material was laid on top of the steel mesh in order to maintain high and uniform moisture at the base of the samples. The anolyte solution was 1M of K_2CO_3. Several reasons brougth about the use of K_2CO_3: the use of granit stones as aggregates, which might lead to alkali-aggregate reactions and the minimization of the potential efflorescences. Electrolytes are substances that facilitate the transfer of electric charge and lead to the production of OH^- ions around the steel bar, causing a restoration of the initial level of alkalinity of the concrete. The electric generator induced an electric current; the intensity of the current was set to a constant 8.54 A/m^2, for a 9 day treatment period.

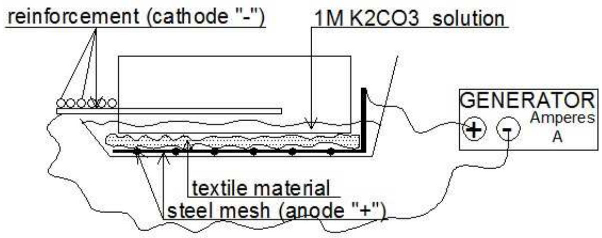

Fig. 14. System design

After the treatment, the prisms were split and sprayed with 1% Phenolphthalein in order to assess the new carbonated layer. The pink color of the concrete after using the Phenolphthalein solution is determined by the basic pore solution and it is inconsistent with the effects of carbonation [17]. The experimental results are shown in Figure 15.

Fig. 15. Prisms after ER treatment

By comparing a fresh split section before the ER treatment (Figure 13) with one after 9 days of treatment (Figure 15), one can see the presence of the pink color at the bottom of the prisms, where the ER was concentrated. Furthermore, after treatment completion, deposits of salt crystals on the reinforcement were also observed, confirming the occurrence of electrochemical reactions, as shown in Figure 16.

Fig. 16. Deposits of salt crystals

It can therefore be observed that, with the acid-base indicator Phenolphthalein, the samples were re-basified and the pH increased up to 10 from a value less than 8, according to previous research. The high porosity of the samples with 0.60 w/c ratio, which was disadvantageous for the ingress of the carbon dioxide, as compared to the 0.40 w/c ratio, also helped accumulate alkaline solution in the ER and controlled a faster repair. Moreover, in the ER the most important effect occurred in the cathode zone, where a flow of OH-ions resulting from the semi-reaction of the water reduction is generated, resulting a higher local increase of the pH level, as compared to zones situated further apart.

4. CONCLUSIONS

The study was focused on proving that the action of the environment can cause serious damage to a structure. The attack of carbon dioxide or chlorides on an infrastructure, such as Calvaria Bridge, is quite inevitable, so, in order to prevent deteriorations - among which the corrosion of the reinforcement is the most significant - it is very important to maintain a high level of quality in both design and construction. In addition, periodic inspections and maintenance procedures must be performed in order to prevent the collapse of an affected member or even of the whole structure. The bridge was investigated through visual inspections and deformations analysis. A repair method, the electrochemical realkalinisation (ER) was also proposed and tested in the laboratory, for two different water/cement (w/c) ratios. Although a w/c ratio of 0.4 seemed less prone to the attack, the results were conservative, at best, because of the high porosity of both 0.4 and 0.6-ratio samples, due to the lack of fine particles in the aggregates. Further testing will be made on the same concrete compositions, but with river aggregates. However, the procedure of realkalinisation was successfully finished, with the carbonated concrete layer restored to normal by the production of hydroxyl ions at the level of cathode. The advantage of this modern repair method is that it can provide effective results in relatively short periods of time, whereas the downside is that it is only suitable for structures in which the corrosion of reinforcement is not installed yet, but the carbonation of concrete is present in the concrete cover. Because the deterioration is passively in hiding and may be hard to observe, basic inspections of concrete structures should include microstructure investigations along with structural macro scale surveys. As future directions of this study, the authors acknowledge the importance of the present research to reach the public officials and to obtain the necessary approvals for an in situ set up of the realkalinisation procedure for stopping further deteriorations in Calvaria Bridge.

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