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Strengthening of concrete structures - Today's green solution for upcoming engineering challenges

Abstract: The use of structural concrete for engineering is often criticized for its CO_2 emission. Nevertheless, concrete is very important for structures, especially for infrastructure, and its use cannot be completely ruled out, nor can it be replaced on a large scale. It is therefore necessary to find ways to reduce CO_2 emission in the building process. One possibility is to extend the lifetime of structures and delay their replacement, as this requires less concrete and reduces the emission of CO_2. A large part of Central Europe's infrastructure was designed decades ago and has different needs regarding strengthening. Over the last decades, a wide variety of strengthening methods have been developed. The resistance of a building component is affected by different parameters. A strengthening method usually increases the resistance of a building component by affecting one or more of these parameters – with it also typically being necessary to strengthen the individual component in order to overcome different deficits. A combination of different strengthening methods is therefore often required. The most common methods for increasing the bending-, shear-, punching- and torsion capacity of structural parts made out of reinforced concrete are described in this article, highlighting the potential that structural strengthening offers for increasing the lifetime of structures and for reducing the impact on the environment of the structure.

1. Concrete and its ecological fingerprint

Structural concrete is one of the most used building materials. It has various advantages as the almost unrestricted shaping, the possibility of producing monolithic connections of individual components, its robustness, its high durability or its fire resistance. Due to the use of relatively inexpensive raw materials available in large quantities and due to the ease of production and processing structural concrete provides a high cost-effectiveness. The main disadvantage is its high dead weight compared to e.g. construction steel and the high thermal conductivity. Besides the monolithic connections make subsequent conversions of the structure difficult [1].

Due to its prevalence in modern construction, concrete has a high responsibility with regard to environmental protection. Especially since its production is often described as very harmful to the environment. According to Sobek [2] the construction industry is responsible for 60% of global resource consumption, 50% of global greenhouse gas emissions, 35% of the world's energy consumption and 50% of the world's waste. Currently, about 4.65 billion tons of cement are used per year. By 2050, this annual consumption is expected to increase by up to 23%. This is due to the demand for construction measures as a result of population growth, urbanization, and infrastructure development and expansion [3]. Sabbie et al [4] point out that the production of concrete results in approximately 8.6% of all anthropogenic CO_2 emissions. Sand and gravel are required for the production of concrete. These are not available in sufficient quantity or quality in every country. This creates the problem that a lot of material has to be transported over long distances, which results in additional emissions. Furthermore concrete has the most rapid increase in consumption among globally common structural materials.

In order to counteract current and future developments with regard to climate and price increases for building materials, the reduction of emissions can be pursued through further development of concrete

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formulations (e.g. fly ash, etc.). On the other hand, it is imperative to design constructions in a material-saving way. To this end, it will be necessary to revive the material-saving designs from the early days of reinforced concrete construction, which have received little attention for a long time. While at the beginning of concrete construction the engineer was concerned to use the material as efficiently as possible, in the last decades the man-hour often became the determining economic factor. This led to the fact that often fast and little material-saving solutions were found. With the need to save material for reasons of environmental protection and construction efficiency, more attention should be paid today to a very material-saving construction method. Material should only be used where it is needed. For example, a combination of ribbed slab and enlarged supporting area can be a material saving option compared to a continuous flat slab. The use of free-form shapes instead of geometrically simple, rectilinear shapes can also be material-saving. On the other hand costs for formwork rise with the difficulty of the shape. In particular, designing close to nature in the sense of bionics will be an indispensable tool for increasing efficiency for future generations of engineers. The bionic optimization of concrete structures by evolutionary algorithms is described in [9].

To reduce the resource consumption and the environmental pollution it is essential to use structures at least as long as they were originally planned for. Reasons as greater volume of traffic in combination with increasing axle loads of vehicles, as well as more restrictive design rules can cause a shortening of the service life. One possibility to extend the lifetime of structures and delay their replacement is to strengthen the structure, as this requires less concrete and reduces the emission of CO_2.

2. The need of strengthening

2.1. Reasons for the need of strengthening

Due to the total resource of built structures and their age, strengthening and restoration become increasingly important. For instance, the Austrian state railway (ÖBB) already uses 56 % of the annual building investments for the preservation of existing structures [5]. Besides the ageing of structures other reasons for a need of strengthening are changes in the design rules, increasing traffic volume in combination with increasing axle loads and a growth in transport volume as well as the reutilization and execution errors or poor maintenance. Moreover, due to the immense costs of demolition and new construction of existing infrastructure buildings, retrofitting should be preferred to replacement construction from an economic point of view as well as for reasons of sustainability. As shown in section 3, a large number of methods for the retrofitting of structural elements have been developed in recent decades.

2.2. Age structure and economic aspects

For the Central European countries, the bridge infrastructure is mostly between 30 and 60 years old. For example 43% of the bridges in Austria were built in the 60s, 70s and 80s which make up 64% of total bridge areas [6]. Every structure is subject to a life cycle from the moment it is erected and thus to originally planned and later unforeseen loads. In many cases, the targeted service life of a structure can only be achieved if the current target condition is restored by repair or the future target condition is achieved by strengthening. Therefore the individual component or the entire structure can only achieve the intended service life if sufficient maintenance investments are made in good time [7]. As an example for a bridge structure, the target service life is usually 100 years. Wicke et al. [7] defined a bridge structure as operative if it has a sufficient load-bearing safety that is according to applicable standards as well as sufficient durability and serviceability.

The cost development for bridge maintenance is shown on the left side of figure 1. Maintenance of the structure begins from the time of completion and remains approximately costless until the end of the warranty period. The subsequent operating phase is characterized by ongoing costs due to maintenance and repair. Depending on the type of structure, general refurbishment occurs once or twice during the operating phase. When the bridge has finally reached the end of its service life, either through obsolescence or overloading, it is usually demolished and replaced. The right picture of figure 1 shows a comparison between the previous approach to the lifecycle of a structure (above) and the desirable future approach (below). Previously the structures were demolished after they had reached their lifetime

- timely or premature due to insufficiencies. The green approach would be to strengthen the structure and thus extend the lifetime and reduce the impact on the environment.

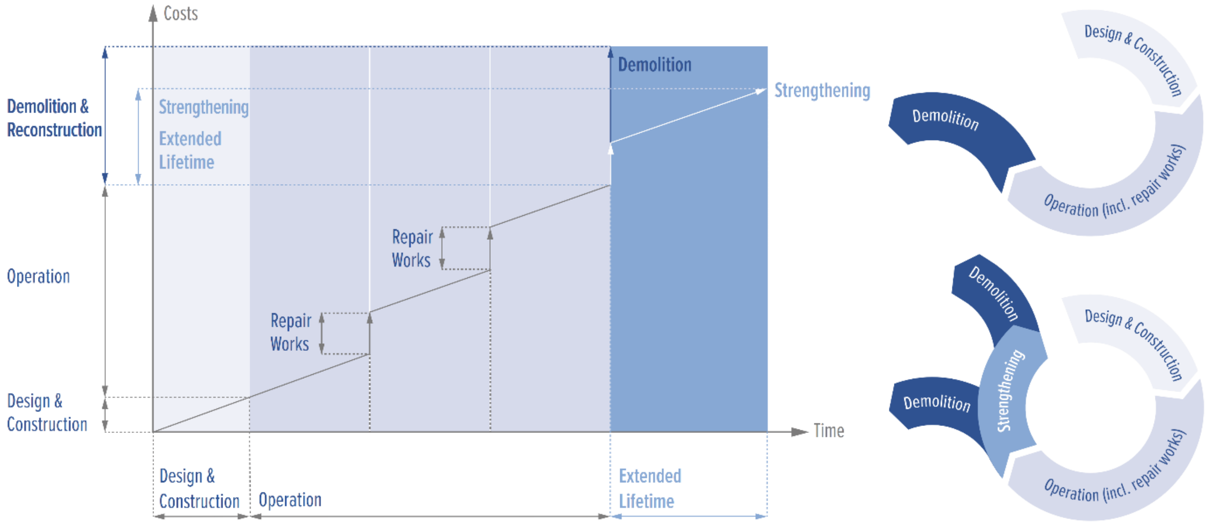


Fig. 1. Life cycle of a structure according to [7] (left) and Current and targeted life cycles for a structure (right)

It can be assumed that it is in the natural interest of the national economy to use a bridge/building as long as possible and to postpone the costs and environmental impacts incurred for demolition and new construction as far as possible. In addition to the cost of replacing the structure, consideration must be given to the costs and problems associated with reduced use. When a bridge is replaced, traffic must be routed with restricted lane use or, in the worst case, rerouted. This results in traffic jams, local traffic congestions and thus economic costs. In addition, the age structure of our infrastructure leads to the fact that many structures reach the end of their service life at the same time, necessitating extensive work on the infrastructure network in close proximity to one another. Through the targeted use of strengthening measures, the time at which replacement becomes necessary can be delayed.

2.3. Change of the occurring loads

In addition to the changing design approaches and load models, as well as the increasing age of the infrastructure, bridge structures are subject to increasing traffic volumes. Over the last decades both rail and road traffic have been increasing and are expected to continue to do so, as exemplified by the traffic over the major Alpine passes. Figure 2 shows the increase of transalpine freight traffic between 1980 and 2018 over the inner Alpine arc (Mont-Cenis (F) / Fréjus (F) - Mont Blanc (F/I) - Simplon (CH) - Gotthard (CH) - Brenner (A)). The graphs show that traffic has increased in Switzerland and Austria. The structures need to be able to absorb the additional loads resulting from the increased traffic.

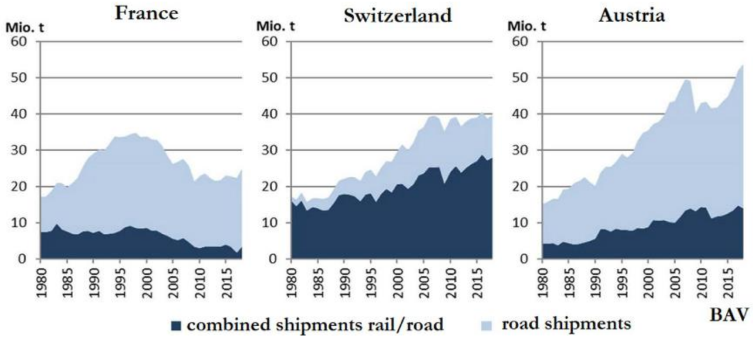


Fig. 2. Development of the transalpine freight traffic between 1980 and 2018 over the inner Alpine arc (from [8])

2.1. Change of standards and load models

Recalculating existing structures with current standards often shows a lack of resistance. Therefore, the required verifications cannot be provided. In the case of shear and punching shear resistance, this is mainly due to the fact that older generations of standards required significantly less shear reinforcement for the same load. Fischer et al. [10] compared the recalculation results of a large number of bridges in the German infrastructure network. They conclude that, on the basis of the recalculation guideline [11], a retrofit or a replacement construction would have to be recommended for 70 % of the examined structures. The fact that some existing structures do not meet current design standards can be attributed to two main factors. On one hand side, as described above, the conditions of use have changed e.g. the volume of traffic, the tonnages transported and the axle loads have increased and are expected to continue to increase. On the other hand, the harmonization of the European standards and codes resulted in more restrictive design rules [1] and [12]. The changed requirements for the occurring loads were taken into account with new load models in the course of the harmonization of European standardization.

2.2. Conditions, defects and maintenance

In addition to the influences described so far, planning errors as well as execution errors can occur and are not always recognized immediately. If the basic principle of ongoing monitoring and maintenance is not observed, even initially small and often insignificant damage can develop into a capital hazard over time. Potentially, the load-bearing capacity can be reduced over time by inadequate maintenance. Structural maintenance is therefore essential.

3. Common methods of strengthening

Due to the steadily growing proportion of existing structures, the strengthening and repair of load-bearing structures has gained in importance over the past decades. Efforts have been made by both universities and the private sector to develop innovative and effective systems to increase the bending, torsion, shear or punching resistance. The resistance of a building component is affected by different parameters. A strengthening method usually increases the resistance of a building component by affecting one or more of these parameters – with it also typically being necessary to strengthen the individual component in order to overcome different deficits. A combination of different strengthening methods is therefore often required. The following sections are intended to provide an overview of typical strengthening methods but no claim is made to completeness.

3.1. Requirements for a reinforcement system

With regard to an economical and technologically reasonable application, a system for subsequent strengthening should meet as many of the following requirements as possible, see [13] and [14]:

- The primary objective of a subsequently installed strengthening system is to increase the load-bearing capacity. A significant increase in resistance should ideally be achieved with the smallest possible number of strengthening elements.
- If failure occurs, the strengthening system should cause this to occur as ductile as possible.
- A subsequently installed strengthening system should be universally applicable. In order to be used in bridge construction, it must be effective under both static and dynamic loads.
- A strengthening system must be characterized by its economic efficiency. Ideally, the system can be installed from one side of the structure to avoid interrupting operations and damage to pavements and seals.
- The element should be anchored slip-free to be activated without major deformation.
- The strengthening elements should be able to transmit force immediately after installation.
- The disturbance of the structure by the installation of the strengthening elements must be as small as possible. The existing reinforcement must not be negatively affected.

- In order to disturb the clearance profile as little as possible and for reasons of esthetics and fire protection few add-on parts should be visible on the components surface.

3.2. Increase of the bending capacity

The load-bearing capacity can be increased by strengthening with concrete. On the one hand, the bending and shear capacity can be increased by applying an additional in-situ concrete layer in the compression zone of the component. The increase in the effective depth leads to an increase in the inner lever-arm and thus to an increase in the ultimate load. The supplemented compression zone must be connected to the existing structure in a shear-resistant manner. The left picture of figure 3 shows a compression flange supplement for a bridge slab. On the other hand, the flexural and shear strength can be increased by supplementing the reinforcement in the tensile zone. The reinforcement can either be inserted into the existing cross-section or connected to the existing concrete by supplementing the cross-section with in-situ concrete or shotcrete. Figure 4 shows an example of cross-section supplementation on a slab beam.

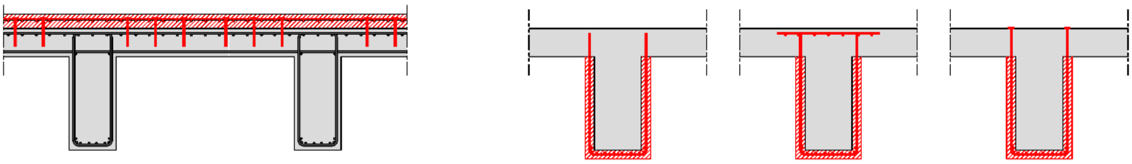


Fig. 3. In-situ concrete layer as strengthening of a slab (left) and cross section supplement for a tee-beam (right, both adapted from [15]).

To insert the required supplementary reinforcement into the existing cross-section, it can also be applied in grooves. For this purpose, grooves are milled into the concrete cross-section mechanically or by high-pressure water jets. The reinforcement is inserted into these grooves and cast using shotcrete or fill concrete. Figure 4 shows the cross-section of a filled groove with typical dimensions.

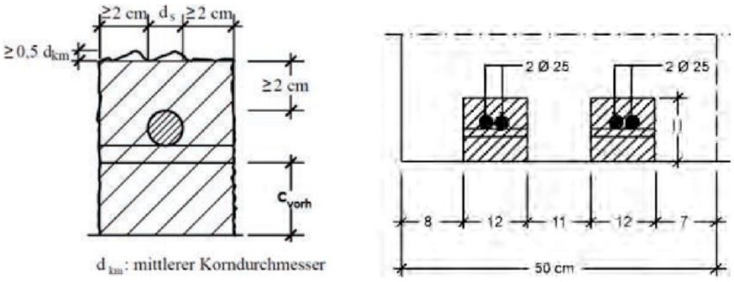


Fig. 4. Example fort the construction of post-installed supplementary reinforcement placed in grouted grooves (right, taken from [15] and left taken from [16]).

Fig. 5. Bonded CFRP laminations on the underside of a cross-section (left) and prestressing of CFRP laminations (right), taken from [16]

Another way of increasing the flexural strength is to attach reinforcing plates to the surface of the existing concrete. These can either be made of steel, but also of alternative reinforcements such as CFRP. The connection to the existing concrete can be made either by bonding, by means of shotcrete or also by bolting or a combination of the above measures. The application can be slack or prestressed. Particularly when using steel straps, care must be taken to ensure appropriate corrosion protection. Figure 5 shows an example of the use of glued-on supplementary lugs made of CFRP lamellas. The use of this variant for strengthening components is described in [12]. Alternatively, CFRP lamellas can also be embedded in slots, see figure 6. The slots are made perpendicular to the component surface and usually mechanically by means of sawing equipment. The lamellas are glued into the slots with epoxy resin adhesive.

The installation of external prestressing can also increase the flexural capacity of a cross-section. Lastly, modification of the static system and load redistribution are measures to be mentioned.

Fig. 6. Reinforcement installed in slots with CFRP lamellae on the underside of a cross-section (left) and slots prepared for installation (right), taken from [16].

3.3. Increase of the shear capacity

According to [13] the systems for subsequently increasing the shear capacity can be distinguished as shown in figure 7. Current methods include supplementary cross sections (b), reinforcement bars or screws that are drilled and glued into the structure (c), externally mounted supporting structures as cross beams with tension bars (d) and externally bonded reinforcement made of CFRP or steel, which can cover the entire surface of a girder (e) or the sides of a girder (f).

Methods for increasing the shear capacity of building components can be classified in different ways. Gross [17] defines a classification with three divisions. Those are firstly the cross-section supplementation including e.g. the classic cross-section supplementation with a supplementary layer of concrete (shotcrete method) in which the additional reinforcement is embedded as well as the application of a much thinner layer of fine concrete with textile reinforcement and the use of externally bolted or glued steel plates. Secondly the reinforcement supplementation including e.g. methods bonding the reinforcement directly to the surface, strengthening by adding bolts, anchors or rebars within the concrete cross section or grooved into the surface as well as CFRP laminations, undercut anchors, concrete screws, rebars and prestressed threaded rods. Thirdly Gross [17] describes methods that do not fall into the previously mentioned categories e.g. external prestressing, grouting shear cracks, the modification of the static system as well as the rearrangement of loads.

The strengthening systems can be classified in various ways. Alternative classifications to the one above are those of Brückner [18], Hegger et. al. [19] or Hellberg et al. [20]. Brückner [18] divides into three types of systems:

- strengthening with additional reinforcement and shotcrete
- strengthening with glued on reinforcement
- strengthening with additional reinforcement grooved into the structure

Hegger et al. [19] divide the systems according to their effects on the structural element:

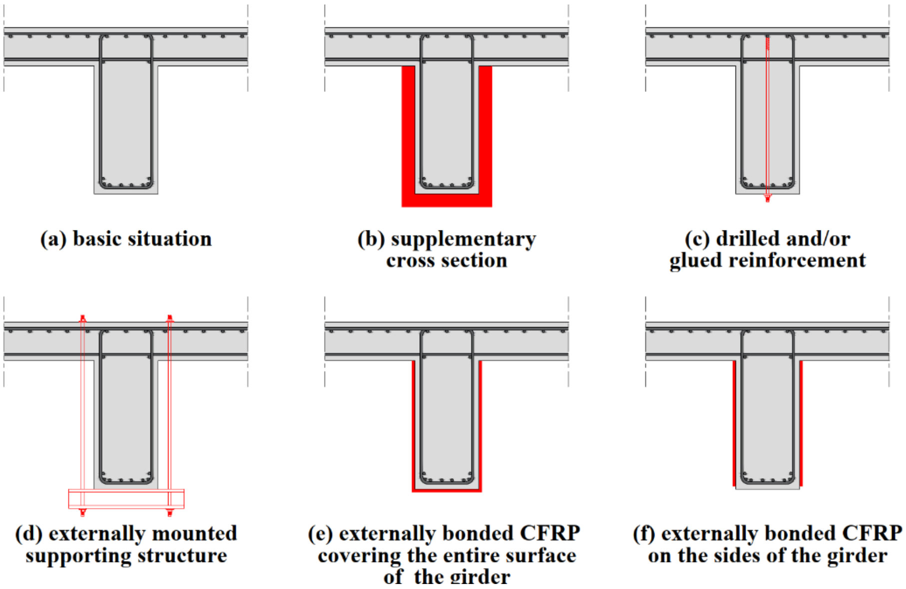
- increase of the membrane forces and normal stresses
- increase of the cross section area/supplementary cross sections

- change of the statical system

Hellberg et al. [20] propose a third method to classify systems according to the materials used for the strengthening elements:

- steel
- fibre composits
- other materials

Strengthening by adding a layer of shotcrete allows high increases in ultimate load. The addition of longitudinal reinforcement and stirrups increases not only the shear resistance but also the bending resistance. The properties of the applied shotcrete can be adapted to those of the component to be strengthened, which guarantees high effectiveness of the system. A disadvantage is the high dead weight of the strengthening layer. This results, among other things, from the concrete cover required to guarantee the required durability of the reinforcement. The amount of work required for removing concrete, preparing/roughening the underground and drilling in the supplementary reinforcement is very time-consuming and may necessitate temporary supports. Systems of this type are described, for example, in [21]. The left picture of figure 8 shows an example for a pre-fabricated reinforcement-supplement later covered with shotcrete.



(a) basic situation

(b) supplementary cross section

(c) drilled and/or glued reinforcement

(d) externally mounted supporting structure

(e) externally bonded CFRP covering the entire surface of the girder

(f) externally bonded CFRP on the sides of the girder

Fig. 7. Methods for increasing the shear resistance (adapted from [13])

If a layer of textile concrete is used for strengthening, the required thickness of the added layer and thus the additional weight can be reduced. Ultra-high-strength concretes and reinforcement made of fiber composite plastics are used, see central picture of figure 8. Due to the corrosion resistance of fiber-reinforced plastics, it is possible to work with significantly reduced concrete cover. In addition, the thickness of the required reinforcing layers is reduced due to the high strengths of concrete and fibers. The high cost of the materials used and the only partially clarified recyclability of fiber-reinforced plastics can be cited as disadvantages. Systems of this type are described, for example, in [23] to [26].

The use of externally attached steel plates as a reinforcing element offers an alternative to the application of additional concrete layers, see the right picture of figure 8. The plates are bonded and bolted to the structure with a shear force deficit. In this way, the load-bearing capacity as well as the serviceability and ductility of the structure can be increased. At the same time, the increase in the original cross-section remains limited. Disadvantages are the high weight of the steel plates, the costly provision of fire resistance, and also the need to ensure adequate corrosion protection of the externally applied strengthening elements. Systems of this type are described, for example, in [27] to [29].

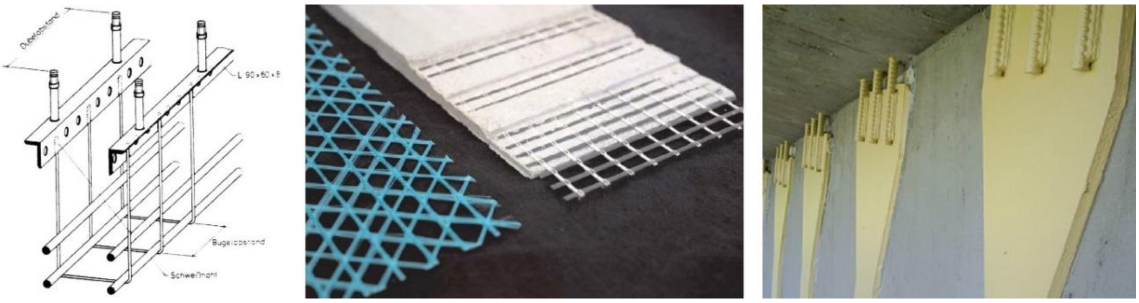


Fig. 8. pre-fabricated reinforcement-supplement to be used on a beam (left, taken from [21]), textile concrete (left, taken from [24]) and externally attached steel plates (right, taken from [22]).

Strengthening by bonding sheets of carbon fiber-reinforced plastics to the structure or by surrounding it with them leads to a significant increase in shear resistance. At the same time, these strengthening elements are very light and only small additional masses are applied to the original structure. The geometry of the cross-section is only increased or changed to a small extent. If the compression and tension zone of a beam are to be wrapped, it is necessary to use special anchoring systems or to drill through the plate. A disadvantage is the sensitivity to the effects of fire of the adhesive as well as the strengthening elements. At excessively high temperatures, both the adhesive and the carbon fiber reinforced plastic sheets lose their strength. Ensuring a force-fit bond between the sheet and the underground requires appropriate preparation of the original concrete. Systems of this type are described, for example, in [30] to [33].

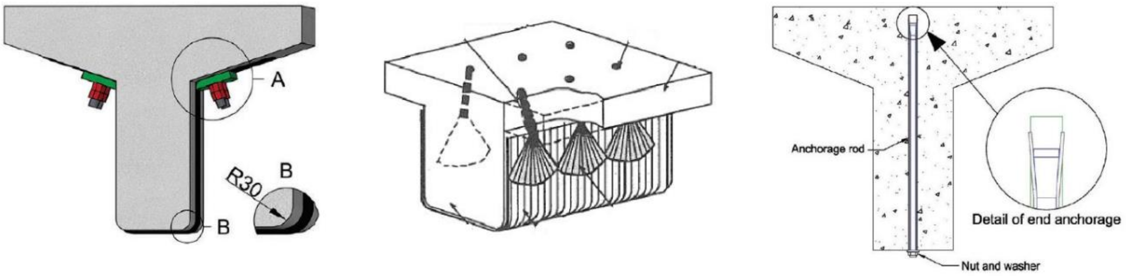


Fig. 9. CFRP-Strengthening of a beam with steel plate and anchors (left, taken from [31]), CFRP with spread up ends for anchoring (center, taken from [32]) and post-installed anchor for shear-strengthening of a beam (right, taken from [32]).

Figure 9 left and center shows two examples for CFRP-strengthening. The use of subsequently installed shear strengthening elements, such as reinforcing bars grouted into boreholes or grooves, concrete screws or undercut anchors, offers the advantage that access to the structural member only has to be ensured from one side. The right picture of figure 9 shows an example for a post-installed anchor for shear-strengthening of a beam. The reinforcing elements are drilled in vertically to the component surface or at an angle. The greatest effectiveness can be achieved if they cross the shear crack at approximately 90°. Work-related traffic blockages on bridges and damage to the sealings can be avoided with this type of system. Ideally, anchorages are used that function on the basis of form closure in combination with adhesive closure. Form-fit ensures that forces are taken up by the element immediately after installation and even before the composite adhesive has cured, so that an immediate strengthening effect occurs. On the other hand, a strengthening effect is maintained even if the adhesive fails due to fire or insufficient cleanliness of the drill hole. Disadvantages include the need to drill holes at an angle and the temperature sensitivity of purely bonded systems. As an alternative to steel reinforcing elements, rods made of fiber-reinforced plastics can be used. The system with subsequently installed concrete screws according to Lechner and Feix [13] does not have these disadvantages.

Heiza et al. [34] showed some effective methods for the strengthening of reinforced concrete columns. The use of steel jackets to increase the seismic performance of columns is a well known procedure that can be implemented in relatively short time. As the jackets are mounted externally the corrosion of the parts has to be prevented. Wrapping the column in multiple layers of fibre reinforced polymers lead to improved strength and ultimate strain of the original concrete. Due to the applied pressure resulting from the confinement the ductility of the system can be improved. The fibre reinforced polymer reinforcement needs to be protected against fire, wear and impact. Debonding failures need to be prevented.

The reader will find a broad overview of the various common methods to increase the shear resistance in the work by Gross [17]. Both purely experimentally investigated systems and those with approval are presented.

3.4. Increase of the punching capacity

Various parameters such as the size of the load application area, the effective depth, the concrete strength and composition, the degree of flexural reinforcement and the quantity as well as the type and arrangement of punching shear reinforcement have a significant influence on the magnitude of the punching shear resistance. In order to strengthen a structural system, it is necessary to influence one or more of these quantities. One possibility to classify punching shear strengthening measures is thus the differentiation according to the influenced parameter. In the studies of Koppitz et al [35], Inacio et al [36], Santos et al [37], Lapi et al [38] and Ramos et al [39] the classification is done according to different aspects, but always in a similar way. According to Lapi et al [38], the classification can be done as follows:

- increasing the load-bearing area (e.g. by concrete or steel mushrooms).
- increasing the bending resistance (e.g. using reinforced concrete or bonded, fiber-reinforced plastics)
- increasing the shear reinforcement ratio (e.g. with subsequently installed steel bolts or glued-in reinforcing bars)
- increasing the bending resistance and/or the shear resistance (e.g. with a top concrete layer)

Based on the considerations of Ruiz et al. [41], figure 10 gives an overview of conventional methods for punching shear reinforcement. The widening of the column head shown in (a) represents an increase in the load application area. This can be done by widening the cross-section with concrete or more frequently with steel attachments, see Luo and Durrani [42] and Hassanzadeh and Sundquist [43]. According to Amsler et al. [44] the effective depth and the flexural reinforcement ratio can be increased by installing a top concrete layer (b). An increase in the flexural reinforcement ratio can also be achieved by bonding carbon fiber lamellas to the tensile area as shown in (c) and described by Faria et al [45]. Other options for increasing the flexural reinforcement ratio are the cross-bonded CFRP laminations with attachment via anchor bolts according to Urban and Tarka [46]. The application of textile-reinforced mortar layers, as described by Koutas and Bournas [47], can also be cited to increase the degree of flexural reinforcement and the effective depth. According to Keller et al. [48], such CFRP lamellas can also be guided through predrilled holes in the slab to act as shear reinforcement. They are used in the form of strand loops that are prestressed and anchored to the underside of the slab [d].

Another way of increasing the shear reinforcement ratio is to install threaded rods (threaded anchors) anchored on both sides in pre-drilled holes. Due to the anchoring to the concrete surface on the top and bottom side of the slab, this system is characterized by very high effectiveness. The possibility of installation from one side only is offered by the system of diagonally drilled and glued-in anchor rods presented by Ruiz et al [41]. The anchors cross the shear crack approximately at right angles and can be installed from below without interfering with (passenger) traffic on the top of the slab. A similar system is the use of subsequently fitted concrete screws proposed by Feix et al. These are installed vertically into the slab. Accessibility is only required from one side. Traffic blockages, damage to the sealing and the difficult production of inclined drillings can be effectively avoided with this system [40]. Stibernitz [49] lists additional systems for increasing the shear reinforcement ratio as vertically installed shear bolts, vertically installed ribbed CFRP bars or CFRP grids and vertically installed CFRP bundles with compartments. The CFRP strand loops shown in (d) strengthen the system by applying prestress. According to [49], other systems of this type would be the installation of prestressed steel strands anchored via composite or prestressed CFRP strands anchored mechanically and/or via composite.

Due to the increase of the supporting area and the effective depth and/or the flexural reinforcement ratio shown in (a) to (c) the deformation capacity of the system is decreased. This leads to more brittle failure, particularly in combination with a lack of shear reinforcement and a lack of redistribution possibilities. Such failure modes are characterized by little to no failure indication and should be avoided. Therefore preference should be given to strengthening systems that result in an increase in deformation capacity. These include the methods shown in Figures (d) through (f), which increase the shear reinforcement ratio. If the aim is to minimize the limitation of usability of the upper side of the slab, solutions (b) to (e) are only suitable to a limited extent. For their implementation, accessibility to the top of the slab is required. For this purpose, the slabs surface must be exposed, which means the removal of pavement, track bed or floor covering. The result is limited usability, which, using a bridge as an example, leads to at least expensive partial closures. Traffic detour, closures, traffic jams and obstructions are associated with high costs and should therefore be avoided. In addition, difficult detail solutions arise with regard to the rearrangement of the structure sealing.

The method shown in (f) with drilled-in and glued-in anchors combines the increase in deformation capacity and the possible installation from the underside of the structure. Thus, it does not require accessibility from the top of the slab. The anchors are bonded with composite mortar into pre-drilled holes made at 45° to the horizontal. On the one hand, inclined drill holes are difficult to make and, on the other hand, it is difficult to ensure that the upper reinforcement layer is not damaged by the drilling process. Due to the difficulty of locating the reinforcement through thick slabs, the risk to damage the reinforcement increases with increasing slab thickness. Another disadvantage of this reinforcement concept is that the system works exclusively with adhesive bond. To ensure sufficient effectiveness of the bonded joint the drilled holes need to be dry and dust-free. The limited temperature resistance of adhesives can also lead to a reduction or even loss of the reinforcing effect. The system with subsequently installed concrete screws according to Feix et al [40] does not have these disadvantages.

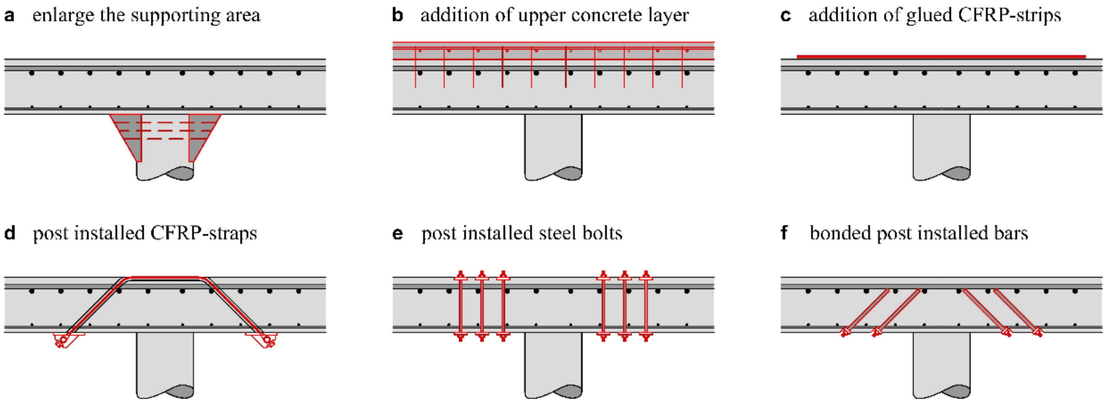


Fig. 10. Methods to increase the Punching Shear Capacity of existing Slabs (taken from [40])

The reader will find a broad overview of the various common methods to increase the punching resistance in the work by Stibernitz [49]. Both purely experimentally investigated systems and those with approval are presented.

3.5. Increase of the torsion capacity

The strengthening of torsion members is usually done by methods similar to those mentioned above. The three usually applied methods are as follows. The torsional capacity can be improved by increasing the cross section of the member in combination with the adding of transverse reinforcement. Different methods mentioned above can be used for that. Alternatively, the use of externally bonded steel plates as mentioned for shear strengthening is a suitable solution. Also, the application of external or internal post-tensioning can be used. The additional tension increases the shear- and bending-capacity as well. The application of external wrap-arounds similar to the strengthening of columns with FRP is another option.

4. Reduced impact of structures on the environment

4.1. Possible reductions

On the one hand the production of the building materials and their recycling can be further optimized. As example various approaches for the concrete and cement industry are stated in [3] or for the steel production in [62].

Another way is to extend the lifespan of existing structures by strengthening to overcome deficits in bearing capacity and adaption for current and future requirements rather than to demolish and build them new. Compared to demolition and reconstruction several advantages and possibilities for reduction of emissions are obvious and some of them are stated in the following:

- The amount and therefor the consumption of energy and resources for the production of the necessary material is reduced significantly.
- Also the transport of material and haul at site are reduced.
- The construction time is shortened which also implies that the impact on the vicinity of the site and traffic obstructions decreased.

In the following chapter a simple example for plate bridges shall show the potential savings which are already significant although only material production and transport are considered.

4.2. Illustration by means of an example using the CMCM

In the following the possible reduction of carbon emissions for concrete bridges is illustrated for a simplified example using the Cement Milkmaid's Calculation Method (CMCM).

We assume an existing concrete plate bridge built in the 1970's in Austria. It was constructed with a concrete strength class B300 which has a characteristic strength of f_{ck} = 17.8 MPa according to [50] which can be roughly characterized as C20/25 according to Eurocode. The used rebar steel category IV has a yield strength of f_y = 500 MPa which equals B500 according to Eurocode.

The single span width is L = 14 m, the width is B = 7.50 m and the construction height is H_c = 0.70 m. The bridge has an area of A = 105 m² and has a road construction height of H_r = 0.20 m. With a weight of γ_c = 25 kN/m³ for the reinforced concrete structure and a weight of γ_r = 24 kN/m³ for the road construction a characteristic dead weight of g_k = 167.25 kN/m is calculated.

The load model for truck loads class I according to [51] has an overall area load of q = 5 kN/m² and a truck load of Q = 250 kN for each lane. The loads have to be multiplied with a dynamic load factor of φ = 1.40 which leads to actions for the single span of m = 1045 kNm/m and q = 252 kN/m for the design.

The load model 1 (LM1) according to [52] for the two lanes with a width of 3 m gives distributed loads of q_1 = 9 kN/m² for the first and q_2 = 2.5 kN/m² for the second lane as well as for the remaining area. The double axes loads are Q_1 = 2 x 300 kN and Q_2 = 2 x 200 kN. With the partial safety factors of $\gamma_g = \gamma_q = 1.35$ the design actions to a moment of m_d = 1536 kNm/m and a shear force of v_d = 349 kN/m are calculated.

The calculation of the required reinforcements with the applicable standards in Austria from the 1970's (ÖNORM [53]) and the current Eurocode [54] gives the results shown inTable *1*.

Table 1: calculated required reinforcement

	ÖNORM [53]	Eurocode [54]	
Moment $a_{s,req}$	62.3 cm²/m	67.3 cm²/m	Assumed to be ok with a refined design calculation
Shear $a_{sw,req}$ (with a_s = 20 cm²/m at support)	3.77 cm²/m²	8.23 cm²/m²	Structural measures needed

To overcome the shear deficit two structural measures are investigated regarding their carbon emission for the transport of material and the used material itself:

- Demolition and reconstruction (D&R)

- Strengthening with subsequently installed concrete screws (S) as shown in Figure 7 as method (c) in chapter 3.3

For the demolition of the bridge with a total weight of some 240 to approximately 14 truck transports for the material and 4 transports for the machinery are assumed. For the reconstruction 11 truck transports are assumed for the concrete (some 95 m³) and 7 transports for reinforcement (some 12 to), formwork and machinery. With a distance to the site of 25 km this calculates to a total distance of 1800 km.

For the strengthening (cements, concrete etc. with 6 m³ and steel etc. with 2 to) a total of 8 truck transports is assumed which calculates to a distance of 400 km.

The calculated emitted carbon shown in

Table *2* is based on the following figures:

- 2.64 kg CO_2/l Diesel for trucks > 18 to with a consumption of 30.8 l Diesel/100 km according to [55]
- 232 kg CO_2/m³ concrete according to [56]
- 482 kg CO_2/to reinforcement steel according to [57]

Table 2: kg emitted carbon per m² bridge area (A = 105 m²)

	demolition & reconstruction	strengthening	Delta D&R - S
Transport	15	5	10
Concrete	210	15	195
Reinforcing Steel	55	10	45
Sum	280	30	250

Not surprisingly the strengthening leads to a massive reduction (some 90%) of the emitted carbon compared to the demolition and reconstruction. To estimate the impact of the reduction on a larger scale the figure is compared with total carbon emissions in Austria in general, for industry & construction and for road construction.

According to [58] there exist some 29000 road bridges with a total bridge area of some 10.5 mio m² in Austria. Some 93.5% of these bridges are constructed with concrete and some 55% have an age between 40 and 60 years. This leads to the estimation that some 51.5% of the concrete bridges in Austria have been constructed in the 1960's and 70' which corresponds to a bridge area of 5.4 mio m².

To estimate the potential applicability for the shear strengthening only as stated in the above example we look at the age structure and bearing states of concrete bridges in Germany that have been investigated by Fischer et al. in [10] and summarize their results for moment and shear bearing capacity in Figure 11.

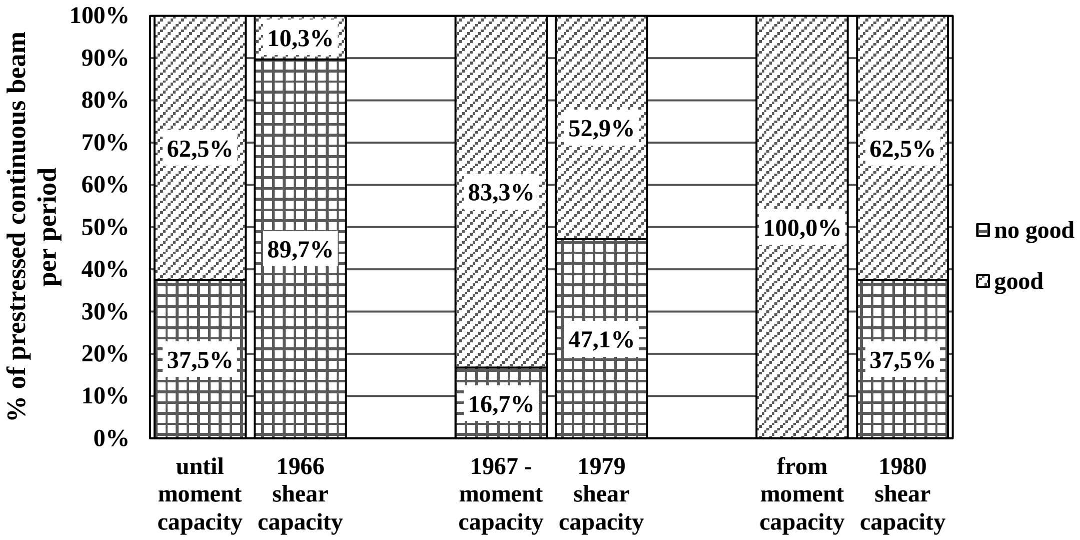


Fig. 11. Bearing capacities for existing bridges in Germany (extracted from [10])

The results show that the main deficit for the investigated bridges compared to the current standards is the shear bearing capacity. For bridges constructed from 1967 to 1979 (age between 40 and 60 years) 47.1% have a deficit in shear capacity where only 16.7% of these bridges have a deficit in the moment capacity. Firstly this gives a validation for the result of the simplified example from above. Secondly we can estimate the portion of the bridges for which a shear strengthening only can be sufficient. With the conservative approach that every bridge with a deficit in moment capacity also has a deficit in shear capacity we end up with 47-17=30%. With the estimate that 1/6 of those bridges cannot be strengthened for other reasons we calculate a potential of 25% for bridges in the age between 40 and 60 years.

For those bridges in Austria this leads to a total area of some 1.35 mio m² and therefor to a total potential reduction of the carbon emission of some 338000 to. Stated that those bridges are strengthened in a period of ten years this give is a potential reduction of 33800 to CO_2/a.

Compared with the total carbon emission that is stated in [59] in Austria with 73.6 mio. to CO_2/a this is a reduction of 0.05%.

According to [60] the sector industry and construction has an estimated share of 15% of the emissions in Germany. Applied to the nationwide emissions in Austria this results in some 11 mio. to CO_2/a for this sector. Compared with this figure the possible reduction can be calculated to 0.3%.

The percentage of the road construction in the construction sector can be estimated with the figures in [61] to some 18% which result in some 2 mio. to CO_2/a. This leads to the proposition that 1.71% or roughly 2% of the annual total carbon emission for road construction in Austria over a period of ten years could be reduced by applying shear strengthening instead of demolition and reconstruction.

5. Conclusions

In this paper, an overview of the current and future challenges and opportunities in the field of solid construction has been given. The role of concrete in construction is a very important one. Due to the greenhouse gases caused by concrete construction, concrete is increasingly criticized in this context. It is not possible to replace concrete, especially since other building materials are generally not CO_2-neutral either. Remedies can be found in modern construction methods, sensible and economical use of the material, and lower-CO_2 cements. One of the most promising approaches is to extend the service life of the structures. This can be achieved by regular repair and investment in the structure and, above all, by strengthening existing buildings.

Besides the environmental aspect the need for strengthening is due to reasons as the ageing of structures, changes in the design rules, increasing traffic volume in combination with increasing axle loads and a growth in transport volume as well as the reutilization and execution errors or poor maintenance. The most common methods for increasing the bending-, shear-, punching- and torsion capacity of structural parts made out of reinforced concrete are mentioned in this article as well as different classification systems and general requirements to strengthening systems.

The possibility of saving CO_2 is worked out in a calculation based on an exemplary bridge structure. The study shows the potential for saving CO_2 by extending the service life. Assuming a strengthening of the existing structure and the resulting elimination of expenses for demolition and new construction, a saving of about 90% of the emitted CO_2 can be achieved in the example presented. About 2% of the annual Austrian CO_2 emissions for road construction could be saved per anno by applying shear strengthening instead of demolition and reconstruction. Depending on the type of the construction (size, span, width, etcetera) the potential can be enlarged.

In the future, construction measures should also be assessed according to their carbon footprint. Further investigations on this field and the different aspects of the dependencies between strengthening and the saving of CO_2 will be needed to evaluate the total potential of strengthening to reduce the CO_2 emissions.

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