Steel fibre combined with conventional reinforcing Joint Free Spillway Chute – Key elements for durability and serviceability

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Spillway structures play an important part in regulating the designed reservoir water level and are paramount to protect the structural integrity of the dam structure. Impermeability and tight crack control are of prime importance in the design and construction of the spillway lining in order to minimise the potential failure modes of cavitation damage and stagnation pressure related failure. A spillway chute is essentially continuously restrained by the roughness of the rock surface and the ground anchors. The provision of control joints, i.e. expansion, contraction and movement joints, are therefore of little benefit due to the restraint as open cracks will still occur. Steel fibre reinforced concrete has been used for resisting erosion of the surface due to abrasion and/or cavitation. Steel fibres combined with conventional reinforcement also provide an amazing synergy to effectively reinforce concrete due to their ability to provide an effective restraining tensile force across open cracks. For the spillway chute, this means any concrete panel size or shape can be considered, even when the chute is fully restrained. Most importantly, this cost effective solution can be constructed joint free while maintaining watertightness. This paper presents some basic principles governing the design of joint free dam spillways employing steel fibre combined with conventional reinforcement. The focus of this paper describes the design and construction of the 400 m long Happy Valley Dam Outfall Channel together with overseas project examples.

Keywords: *Spillway, joint, crack, abrasion, cavitation, steel fibre.*

Introduction

Ensuring that dams are safe and do not pose an unacceptable risk to the public are essential goals for a dam owner. Spillways are designed to provide water release from the dam in a safe manner and to prevent overtopping of a dam at a place that is not designed for it. Although the safety of a dam is evaluated thoroughly, spillways sometimes receive less attention than other features. Failure of a spillway has potentially serious consequences, which can include loss of reservoir storage, loss of life, and downstream damage as evidenced by the spillway damage at Oroville Dam in February 2017. The near-collapse of the Oroville Dam in Butte County, California, United States, if failed, could have been catastrophic by sending a 9 m wall of water cascading through California communities as far as 100 miles downstream from the dam and resulted in US$ 21.8 billion in structural damages (McDonald, 2017).

Understanding and properly assessing the conditions that could lead to failure of a spillway during a flood can help dam owners and engineers to formulate defensive measures and minimise the likelihood of spillway failure when designing a new spillway or modifying or upgrading existing spillway. Many spillways for large dams are designed and constructed with hydraulic control structures, such as a weir, ogee crest, or gated structure, with a section of reinforced concrete lined chute downstream. In addition to providing sufficient discharge capacity, spillway chutes need to resist the design loads, prevent and limit cavitation damage and stagnation pressures, caused by defective joints and/or open cracks, which can lead to hydraulic jacking or structural collapse of the spillway chute which can develop into a condition of head-cutting, leading to loss of the reservoir storage (Trojanowski, 2008; Fiedler, 2016).

Stagnation pressures

Stagnation pressure related spillway failures can occur as a result of water flowing into open cracks and joints within a spillway chute during spillway releases (Trojanowski, 2004; USBR 2007). A portion of the velocity head from the flow can be converted to an uplift pressure under the chute slab if vertical offsets exist such as an open joint. Water can also pass through a joint or open crack, which can result in erosion of foundation material and the build-up of excessive uplift pressure under a concrete slab can also cause hydraulic jacking. Figure 2 depicts the development of stagnation pressures under a spillway chute slab.

Model tests conducted by USBR (2007) suggested that a joint offset of 3 mm together with a 3 mm gap in a joint can develop significant pressures and flow. The study has indicated that pressures and flows into joints with offsets into the flow direction increase with flow velocity. Smaller joint gaps with relatively large offsets may also result in more flow through the joint as compared to a larger gap with smaller offsets. It is also postulated that some flow and pressure could also be developed in a joint without an offset. Undoubtedly from the tests, for a stagnation pressure failure mode to initiate, there needs to be an open crack or joint where flow and/or pressure can enter and access the foundation interface together with an offset into the flow.

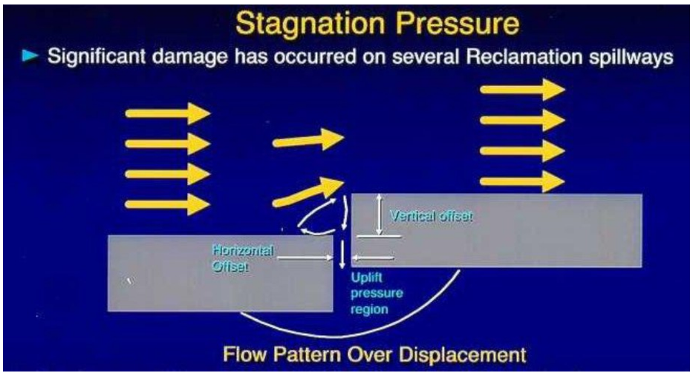


Figure 1. Stagnation pressure development (USBR & USACE, 2015)

Cavitation

Cavitation is the formation of vapour cavities in a liquid. Cavitation occurs in high velocity flow, where the water pressure is reduced locally because of an irregularity in the flow surface (USBR & USACE, 2015). Typical examples of irregularities in spillway chute include offsets into and away from the flow, holes, grooves or open cracks and joints. As the vapour cavities move into a zone of higher pressure, they collapse, sending out high pressure shock waves. If the cavities collapse near the surface of the spillway chute, they can abrade the concrete and an elongated hole will form in the concrete surface after a period of time. The hole will get longer as high velocity flow impinges on the downstream end of the hole. This flow creates high pressures in micro-fractures in the concrete, formed around individual pieces of aggregate and creates pressure differentials between the impact zone and the surrounding area, which can cause aggregates or spalls of concrete to be broken from the surface and swept away in the flow. As erosion from the high velocity flow continues, the surface roughness increases and eventually reinforcing bars may become exposed. Vibration of the exposed bars due to the flows may lead to mechanical damage of the concrete locally and fatigue failure of the reinforcing bars. If flow velocities are sustained, the concrete can be completely removed over a portion of the chute, exposing the underlying foundation leading to foundation erosion.

Defective joints and open cracks

Defective joints and open cracks are some of the precursors to spillway chute cavitation damage and stagnation pressure related failures. Further, open defective joints and wide cracks will also allow seepage flows from the spillway chute into the foundation. These seepage flows may contribute to foundation erosion or scour when the spillway is operating.

Many studies, including Bozorgzadeh (2012), Kanitkar et al. (2011), Ziari and Kianoush (2009), to mention a few, have been undertaken on the flow of water through cracked concrete or an open joint. Their experimental results indicate that the leakage of water through a joint or crack depends on the pressure gradient (i.e. ratio of water depth pressure to the thickness of the concrete section) and opening width and thickness of the concrete. For a 0.1 mm gap opening, Bozorgzadeh (2012) measured a leakage flow of 0.04 *l*/min/m (litre per minute per metre width) when subjected to a pressure gradient of 29. With a pressure gradient of 30, the leakage rates increased exponentially to 57.8 *l*/min/m and 414 *l*/min/m when the gap openings are 1.1 mm and 3.3 mm, respectively (Kanitkar et al., 2011). On the other hand, however, Ziari and Kianoush (2009) observed that a crack as wide as 0.25 mm can partially remediate itself through the autogenous self-healing process when it is exposed to a flow of water through the crack. For a spillway, it will be likely to be subjected to high flow velocity and a 0.25 mm wide crack may not be necessarily self-heal.

Structural defects and damage of the spillway chute joints can take several forms as discussed in USBR & USACE (2015) and cause the joints to open and provide leak paths. In addition, there may be offsets due to thermal curling of the spillway chute and/or foundation heave or settlement.

When insufficient or no expansion jointing has been provided and the reinforcement is not continuous through the joint, delamination can occur near the surface, above the top layer of reinforcement when the spillway chute is exposed to direct sunlight, which generates a thermal gradient through the section resulting in differential thermal strains. Reinforcement parallel to the surface creates a plane of weakness due to the reduced concrete area and a "splitting" tensile force parallel to the surface can occur as shown in Figure 2. It is also worth noting that if the reinforcement is continuous through a joint, the joint is a construction joint and not an expansion or contraction joint as the concrete is bonded and restrained by the continuous reinforcement and expansion or shrinkage strains cannot be alleviated. For this reason, the concrete has to be designed for crack control.

Spalling at joints may be caused by freeze-thaw damage, alkali-aggregate reaction (AAR), lack of concrete cover, or poor concreting techniques, such as lack of concrete compaction or early finishing before the majority of bleed water has escaped. When spalling occurs, a deep localised offset will be present.

Waterstops are typically used as a defensive measures to block the path for water flow through joints in a spillway chute or other water retaining structure. If the waterstop is not flexible, which may be the case for metal waterstops or aged and brittle PVC or rubber waterstops, differential movement at the joint may damage the waterstop. More often in practice, waterstops fail due to being improperly positioned, folded over during concrete placement and/or being incorrectly welded or joined, especially at joint intersections, which require ‘T’ or ‘X’ joints.

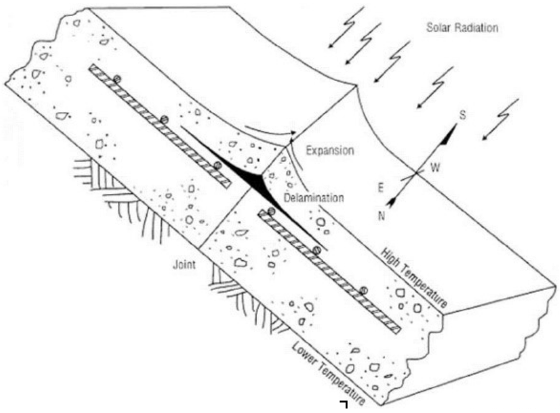


Figure 2. Delamination near spillway chute surface due to solar radiation induced expansion of concrete (USBR, 2014).

Oroville Dam spillway damage crisis

The damage to the spillway of Oroville Dam prompted the evacuation of more than 180,000 people living downstream and the relocation of a fish hatchery. The dam fortunately did not collapse, but the damage to the spillway was significant and sparked tensions and concerns amongst communities and stakeholders, which resulted in the dam owner being heavily scrutinised.

As of July 2017, investigation work was still on-going to determine the cause of the spillway damage. The Oroville Dam Spillway Incident Forensic Investigation Team (2017), however, has identified 24 physical factors that are being considered as potentially contributing to the damage. Of these 24 factors, half of them or 12 of the factors are related to the joints or cracks in the spillway chute. These are:

i. Thinning of the chute slab above herringbone drains; these locations can promote cracking.
ii. Large variations in slab thickness resulting in cracking due to geometrical and stress concentration.
iii. Limited slab reinforcement consisting of one layer of light reinforcement in the top of the slab.
iv. Lack of continuous tension reinforcement across slab joints.
v. Corrosion and failure of reinforcing bars across cracks.
vi. Slab joints with insufficient keys or lack of keys.
vii. Slab placement sizes which were too large to control cracking.
viii. Lack of waterstops in slab joints.
ix. Hydraulic pressures and flows transmitted beneath the slab sections through open cracks and joints.
x. Herringbone drains crossing joints in the slab.
xi. Lack of durability and effectiveness of slab repairs.
xii. Spalling and/or delamination of concrete at slab joints.

As shown in Figure 3, the spillway chute has failed at the joints, which appear to be the weakest section.

Defective joints and open cracks are the Achilles’ heel in spillway chutes. Joints in spillway chutes can work effectively, if detailed and constructed properly, but may require on-going maintenance. Figure 4 presents some typical spillway chute deficiencies mainly due to joints and open cracks. Being able to minimise or eliminate joints and open cracks is an attractive proposition in terms of dam safety and obviously the dam owner’s on-going maintenance costs.

In this paper, the design approach for joint-free continuous reinforced concrete spillway chutes is presented together with case studies both in Australia and internationally. This design concept is not new, however, innovation in the field of concrete design has led to the development of design rules that enable the use of steel fibre reinforced concrete (SFRC) in combination with conventional reinforcement. This improves the engineering efficiency and makes it possible to design cost effective spillway chutes without compromising on quality and dam safety.

Figure 3. Structural collapse of Oroville spillway; note the failure through joints.

Design of joint-free continuously reinforced concrete spillway chutes

General

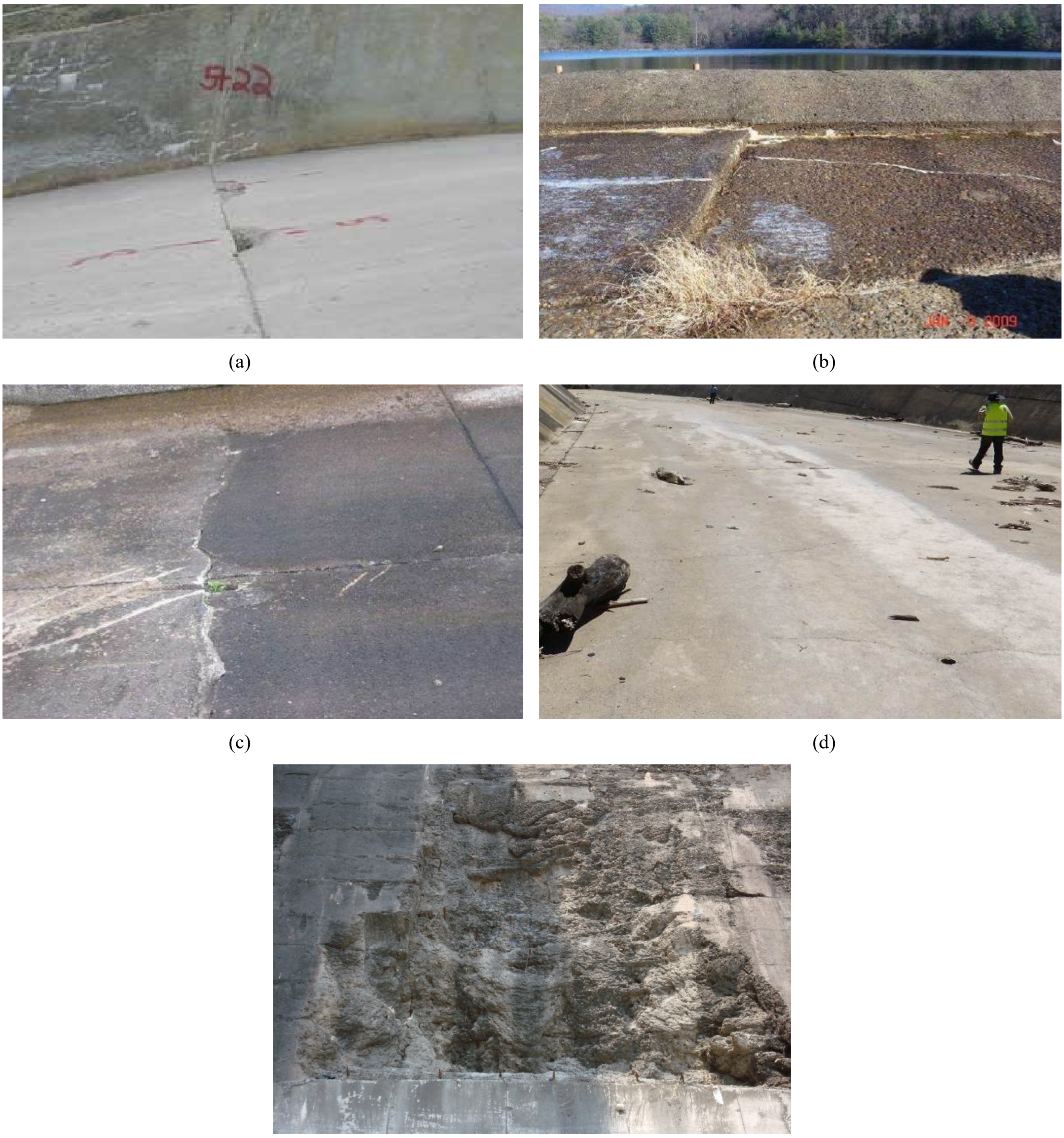
Concrete is a brittle material. Cracking in reinforced concrete is a normal phenomenon. Reinforcement is designed so that cracking due to the early and long term thermal, shrinkage and load induced strains can be controlled. Joints are typically introduced to reduce or eliminate restraint and thereby eliminate the need for large amounts of crack control reinforcement. Dam spillway chutes are generally constructed on clean but rough and irregular rock foundation surfaces and anchored into the foundation, which results in the concrete being continuously and fully restrained and the provision of joints are therefore of little benefit, due to the restraint, as open cracks will still occur and can be observed in most spillway chutes.

Most concrete cracks in spillway chute are intrinsic; due to load-independent deformation, including deformations due to early-age thermal strains, shrinkage and long term ambient temperature changes. During a flood event, structural cracks may also occur in the spillway chute due to the imposed water loading or uplift pressure. If care is not taken during construction, cracking can also occur before final set of the concrete due to early-age heat of hydration, plastic shrinkage or plastic settlement. Defects or cracks that occur when the concrete is in the plastic state may also provide the initiation point for longer term drying shrinkage cracking.

Cracks occur wherever and whenever the tensile stress in the concrete exceeds the tensile strength of the concrete and indeed, it does not take significant force to crack concrete. For instance, if the coefficient of thermal expansion of concrete is $10 x 10^{-6}$, it only takes 680 $\mu\varepsilon$ to initiate a crack in an unreinforced 1m x 1m 32 MPa grade concrete section, which has a Young's modulus of 30.1 GPa and a tensile strength of 2.03 MPa at 28 days. This corresponds to a temperature differential of only 6.8 ^{o}C without taking into account any shrinkage in the concrete. Therefore, instead of attempting to prevent the formation of cracks in concrete, a better and more practical approach is to design and control the cracks within specified levels so that they are not detrimental to the integrity of the structure and do not affect the serviceability and durability of the structure. For spillway chutes, continuous and sufficient reinforcement is provided so that the cracks are tight enough to prevent water flowing through them. The concept of continuously reinforced concrete is not new. It has been used for decades in the continuously reinforced concrete pavement construction, which can extend, joint free, for many kilometres.

Crack width

The Australian concrete structures for retaining liquids code – AS 3735 (2001) limits the steel stress in the reinforcement to ensure that the mean crack widths of 0.1 mm for direct tension and 0.15 mm for flexure are not exceeded. European standards (BS EN 1992-1-1 (2004); BS EN 1992-3 (2006)) suggest that a limit of 0.2 mm on the maximum crack width will provide watertight slabs when the pressure gradient is low, but significantly lower crack widths may be required as the pressure gradient increases, as shown by Figure 5. This is based on research that shows autogenous crack healing capacity at different pressure gradients. Fine, tapering cracks will heal and seal themselves as water penetrates through the crack. Calcium hydroxide salts are dissolved from the cement matrix and, on contact with carbon dioxide in the atmosphere andcrystals of calcium carbonate will be deposited in the cracks. This form of autogenous healing, can be effective at sealing cracks.



(a) (b) (c) (d) (e)

Figure 4. Typical deficiencies in spillway: (a) Spalling of the spillway joint at Scofield Dam USA (Trojanowski, 2008); (b) Offset spillway joint at Stoney Creek Dam USA (Paxson & Young, 2010); (c) Cracked spillway at Colyer Lake Dam USA (Paxson & Young, 2010); (d) Restrained open cracks between joints at an Australian Dam; (e) Cavitation damage at Nagarjuna Sagar Dam India.

In terms of corrosion of steel reinforcement, experience suggests that cracking perpendicular to a reinforcing bar does not in itself constitute a risk of subsequent corrosion unless the crack width is excessive, but cracks parallel to a bar may. Beeby (1978) states "*There is no indication that a structure designed to have, say, 0.3 mm wide cracks will be any worse from a corrosion point of view than one designed to have only 0.1 mm cracks*". However, the likelihood of chloride induced reinforcement corrosion should be durability assessed for crack widths greater than 0.2 mm.

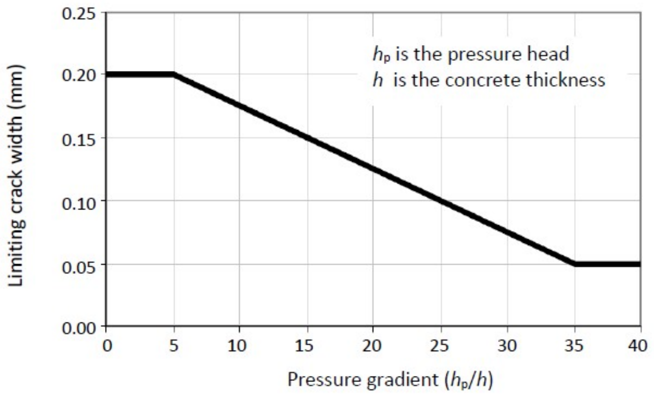


Figure 5. Limiting crack width for self-healing related to pressure gradient across the cross-section (BS EN 1992-3, 2006)

Design philosophy – Conventional reinforcement approach

The current Australian Standards dealing with concrete structures, such as AS 3600 (2009) Concrete Structures, AS 3735 (2001), AS 5100.5 (2017) – Bridge Design: Concrete, which is also used for designing concrete structures requiring a 100 years design life, controls cracking by limiting the maximum tensile stress in the steel reinforcement at the crack, together with certain detailing requirements. This is convenient for designers, but is not always reliable and does not give guidance on predicting concrete crack widths. Section C9.4.3.4 of AS 3600 Concrete Structures – Commentary (2014) states:

> *"The areas of reinforcement specified in this Clause are minimum areas. It is recommended that the area of reinforcement provided always exceed these minimum values. The stated values are independent of the level of shrinkage in the concrete or the temperature changes likely to be experienced by the slab. In some situations, therefore, the specified minimum values may not be adequate for crack control."*

At present, British Standard 8110-1 (1997), European Standards such as BS EN 1992-1-1 (2004), Construction Industry Research and Information Association United Kingdom (CIRIA) C660 report (2007) and Concrete Institute of Australia CIA Z7/06 guidelines (2017) have provided design guidance on predicting concrete crack widths for over 30 years. The principle is based upon the tension chord model (Marti et al., 1998) where the width of a crack is a function of the distance between cracks and the distance between cracks is determined by the bond length of the reinforcing bars; this is shown graphically in Figure 6 and explained below.

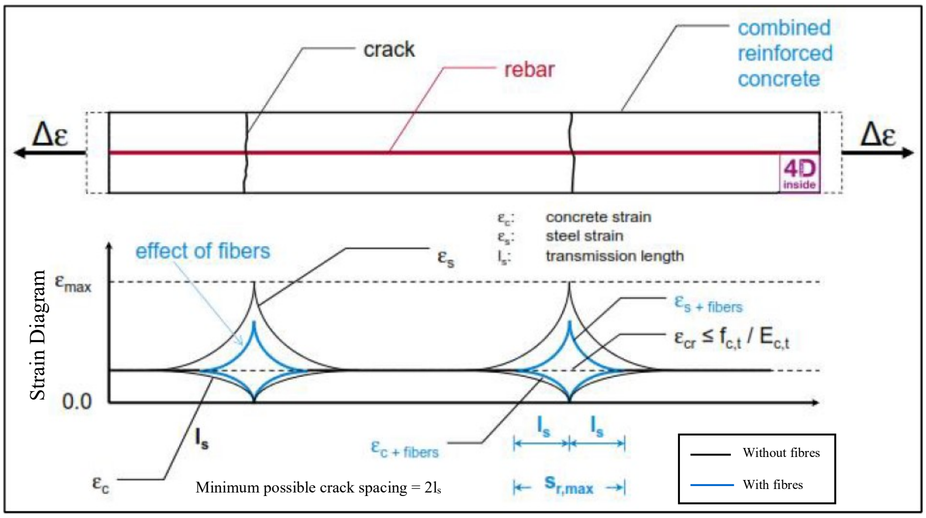


Figure 6 Crack Initiation Phase

(With steel fibres, the strain on the conventional reinforcement reduces, the development length is shorter, the minimum crack spacing (i.e. 2 times development length) is smaller, and, hence, crack width is narrower)

At a crack the tensile force in the concrete is zero with all the tensile force being carried by the reinforcing steel. Away from the crack the reinforcing bars, being effectively bonded into the concrete matrix, transfer this tensile force into the concrete, with all the force being transferred into the concrete a distance from the crack equal to the reinforcing bars development length. This means that the minimum spacing between cracks is two development lengths, which corresponds to the maximum crack width.

Space in this paper prohibits an extensive review on the crack design methodology. Readers are referred to appropriate references when more detailed information is sought.

(It should be noted that AS 3600 – Concrete Structures Draft for Public Comments released on 21st August 2017 has included a crack width design approach, based on the concept described above.)

Design philosophy – Steel fibre reinforced concrete with conventional reinforcement approach

Adding steel fibres to concrete is not considered as new or novel; in the early 1960s, steel fibres were used to improve the tensile strength of concrete. The most important property in steel fibre reinforced concrete (SFRC) is its post-cracking tensile strength. Steel fibres are active as soon as micro-cracks are formed in the concrete. The fibres are able to bridge the crack, transmit stress across the crack and, in the process, provide some resistance to the widening and fracture process of the crack. Thus, unlike plain concrete, an appropriately reinforced SFRC structural element will not completely fail after crack initiation but some residual strength after cracking will be available.

AS 3735 Commentary (2001) recommends the use of SFRC to provide hydraulic abrasion resistance of a concrete surface that is subject to turbulent flow containing debris with high flow velocities. The International Commission on Large Dams (ICOLD) has published a special report on SFRC used in dams in 1982. The principal application is in shotcrete and for high toughness concrete to provide resistance to cavitation and erosion damage. SFRC can increase the resistance to cavitation damage by threefold and improve the resistance to the shattering and crushing effect of boulders and debris by five to ten times. Some of the dams that used SFRC technology for improving cavitation and erosion resistances include Opuha Dam downstream weir in New Zealand, Libby Dam and Lower Monumental, Fort Scott Dams in United States, Nagarjuna Sagar Dam in India, Xiao Wan Dam in China, Koprubasi, Berke, Sir and Akkopru Dams in Turkey, Stadsforsen Dam in Sweden, to list a few.

The Australian Standard for the design of Concrete bridges (AS5100.5, 2017) was released on 31st March 2017; this is the first standard in Australia to include procedures for the design of SFRC structural elements. The new AS 3600 Draft for Public Comments code released on 21st August 2017 also includes procedures for the design of SFRC structural elements.

For crack width design, the post cracking tensile capacity of the SFRC carries part of the tensile stress in the concrete at a crack. As a consequence, the tensile force in the reinforcing bars at the crack is reduced and the development length of the reinforcing bars is consequently reduced (Figure 7). The same holds for the strain in the reinforcing bars. Reducing the development length and the strain of the reinforcing bars reduces the maximum distance between cracks and thus results in more but narrower cracks (Figure 6). For a given crack width, the use of steel fibres can thus significantly decrease the required amount of reinforcing bars.

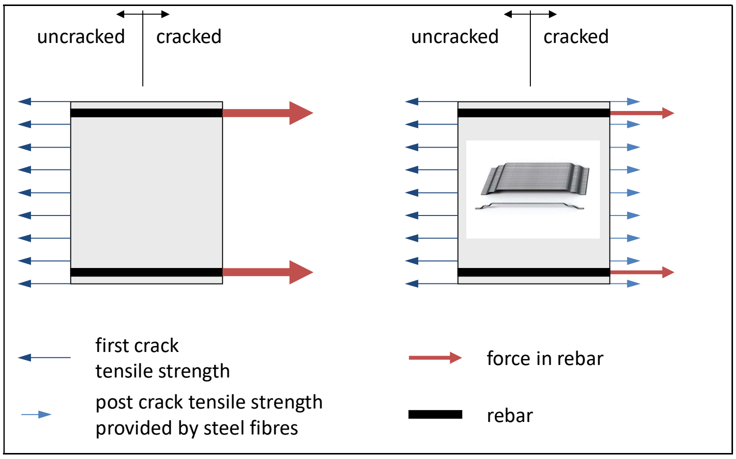


Figure 7. Stress in a cracked reinforced concrete section.

The crack width design approach for SFRC combined with conventional reinforcement corresponds with the method used for conventional reinforced concrete with the rules amended by the post crack tensile strength provided by SFRC. As a simplification of this concept the crack width, w_k, may be seen as a function of the concrete tensile strength, f_{ct}, in the case of reinforced concrete and a function of the concrete tensile strength minus the cracked tensile strength of SFRC, $f_{ct,SFRC}$, in the case of combined reinforcement, this is shown in equation (1):

$$w_k = \text{function}\,(f_{ct} - f_{ct,SFRC}) \quad (1)$$

Apart from serviceability and the determination of crack widths, the post crack strength of SFRC may also be taken into account for the ultimate limit state, where significant contributions to the load carrying capacity are possible.

Example – technical and cost comparisons

As a hypothetical example, a spillway chute slab is 400 mm thick and is designed to have crack widths of less than 0.15 mm. Table 1 below presents the spillway chute slab design based on both the conventional reinforcement and SFRC with conventional reinforcement solutions together with the indicative construction material costs. All design methods based on Australian Standards significantly underestimate the crack width. Based on the European Standard BS EN 1992-1-1 (2004), N24 reinforcement at 150 mm spacing, placed top and bottom, will be required in order to achieve crack widths of 0.15 mm or less. Using high performance steel fibres, much smaller and lighter reinforcement is required, i.e. N12 reinforcement at 140 mm spacing, placed top and bottom, while keeping crack widths at the same level. As a consequence, the reinforcement placing process will become less complicated, more accurate and faster. Placing and compacting concrete due to less congestion of reinforcement also becomes easier with more favourable results being likely.

Table 1. Technical and cost comparisons for of different continuously reinforced concrete chute slab design approach.

Design Approach	**Conventional Reinforcement Design**				**SFRC with conventional reinforcement**	
Design Method	**AS 3600**	**AS 5100.5**	**AS 3735**	**BS EN 1992**	**BS EN 1992**	
Concrete grade	32 MPa	32 MPa	32 MPa	32 MPa	32 MPa ^	32 MPa ^
Steel Reinforcing both sides	N20-200	N20-180	N24-200	N24-150	N12-140 ^	N12-120 ^
Design crack width	**0.40 mm**	**0.32 mm**	**0.25 mm**	**0.13 mm**	**0.14 mm**	**0.10 mm**
Meet crack width criteria?	**NO**	**NO**	**NO**	**YES**	**YES**	**YES**
Ultimate moment capacity	**198 kNm/m**	**219 kNm/m**	**278 kNm/m**	**362 kNm/m**	**192 kNm/m**	**209 kNm/m**
Mass of steel per m^2 of slab	44.4 kg	49.3 kg	67.1 kg	85.2 kg	22.8 kg	26.6 kg
Mass of fibre per m^2 of slab	-	-	-	-	14 kg ^	14 kg ^
Reinforcement + fibre cost per m^2 of slab *	**$ 88.80**	**$ 98.60**	**$ 127.85**	**$ 170.46**	**$ 87.66**	**$ 95.27**

^ using a proprietary high performance double hooked fibres with a dosage rate of 35 kg/m^3
* Indicative reinforcement and fibre cost excludes concrete, labour, time, carnage & transportation, wastage, etc.

Often in hydraulic structures like spillway chute slabs, serviceability limit state design governs the overall design. More reinforcement is typically required for crack control than for strength. The ultimate moment capacities for both the conventional reinforcement and SFRC with conventional reinforcement solutions are also presented in Table 1 for the reader's information.

The SFRC with conventional reinforcement solution costs only half that of the conforming conventional reinforcement solution in construction. Even better, the SFRC with conventional reinforcement solution can also achieve a much tighter crack width of 0.1 mm with much lower cost. Very often, short construction time, construction flood management and the requirements for a high quality end product all conflict with each other on a dam construction site. In the case of SFRC with conventional reinforcement, durability, serviceability and construction time may be improved in one pass. Savings on maintenance costs may therefore also be achieved. Hence, it makes good sense to evaluate the costs, and also the savings, over the full life time of a spillway chute slab.

Steel fibres also reinforce the concrete surface to provide resistance to abrasion, cavitation and spalling as discussed earlier, which is definitely not the case for conventionally reinforced concrete alone. Also, due to the ability of SFRC to resist cracking due to early thermal strains and shrinkage, the cover to normal reinforcement can be increased thereby providing additional resistance to the long term initiation of conventional reinforcement corrosion due to mechanisms such as carbonation and chloride diffusion.

The long term durability of SFRC has been well documented. When steel fibres are mixed in the concrete, the fibres are coated with cement paste. The presence of the free lime (calcium hydroxide) around the steel fibres provides good corrosion resistance to the SFRC. The small diameter of the steel fibres, less than 1 mm, with their large surface area to volume ratio, are more effectively screened by the lime rich layer than the large diameter bars used in conventional reinforced concrete (Wei et al., 1986). In terms of carbonation, the fibres may lose their protective passivating layer in the longer term, but the fibres located deeper remain safe. It has been established that in the long term, steel fibre corrosion is limited to a depth of some 2 mm to 5 mm, depending on the concrete quality (Kern & Schorn, 1991; Nemegeer, 2000). In addition, unlike conventional reinforced concrete, the potential for spalling is virtually non-existent, as steel fibres have a small diameter, if corrosion occurs, the expansive stress due to the generation of corrosion products is so small as to be non-existent (Nemegeer, 2000).

An additional benefit of using SFRC in combination with normal reinforcement to limit the crack width and thereby increasing the watertightness of the concrete, is the increase in resistance to Alkali Aggregate Reaction (AAR) and a form of internal sulphate attack commonly referred to as Delayed Ettringite Formation (DEF). Both of these phenomena can only progress when water is available for the various reactions to occur. By limiting the crack width to less than 0.2 mm and allowing autogenous healing to occur within a crack, the ingress of water into the concrete is minimised, thereby preventing the reactions that cause expansion, which can often result in spalling or cracking.

Case Study – Happy Valley Dam Outfall Channel South Australia

Overview

The Happy Valley outfall channel was an unlined cut through natural soils and rock extending from the southern abutment of the Happy Valley Reservoir. The channel is an extension of the catch drain around the reservoir, and doubles as a spillway in times of flood as shown in Figure 8. The channel is steeply inclined. Vertical alignment is not uniform, being 3% in the upstream, steepening to 8.5% in the central section and flattening to 3% at the downstream end.

The flow in the channel is mainly derived from a developed urban catchment, which utilises the Happy Valley reservoir as a retarding basin at high flows. Because of the urban catchment, the flow regime during winter is usually a low persistent flow in the channel. Floods are likely to be "peaky" because of the high runoff in the urban catchment, and are expected to be of short duration (i.e. less than 24 hours). Since 2003, flows had carved out the bed and banks of the unlined channel. The erosion had undercut and destabilised the banks, causing some trees to fall into the channel. The channel bed was undermined, in some cases up to 8 m below natural surface (Figure 9). In addition to high public access safety risk, blockages of the channel were very likely due to fallen trees and soil build-up. This could result in overtopping of the channel banks and flooding of local residential houses during a 1 in 100 AEP flood event. With more extreme flood events, there was also the potential that dam safety would be compromised, i.e. overtopping of the dam (PWC, 2014).

Figure 8. Site location.

The asset owner has undertaken the remediation work to line and stabilise the channel using reinforced concrete and, hence, reduce the risks. The design flow adopted for the remediation work was 31.8m^3/s, which corresponds to the 1 in 100 AEP flood flow based on the hydrological study for the dam (SKM, 2013). A variable channel profile was adopted based on the existing channel geometry. The outer edges of the bed follow the existing alignment as closely as possible to minimise earthworks.

Hydraulic assessment

HEC-RAS computer software was used to model and assess the hydraulic performance of the modified channel profile and in particular to evaluate the flow velocity and depth. Various energy dissipation solutions such as slab drops, drop structures and weirs (or nib walls) were incorporated into the modelling to mitigate the high velocities typically developed in the channel due to the inherent steep grades and high flows. Based on the modelling, the flow velocities can reach almost 9 m/s with a minimum of around 1 m/s and flow depths range from 0.35 m up to 2.1 m during the 1 in 100 AEP flood event. Hydraulic jumps were also modelled to occur at the various locations due to the convergence of the channel bed width and the inclusion of nib wall weirs to dissipate the energy at the downstream end.

Structural design

The concrete lined spillway channel is subjected to uplift forces due to buoyancy ("bathtub" effect from groundwater or subsoil pore water pressures) and conversion of velocity head pressurising the underside of the slab. These uplift forces are counter balanced by the inherent weight of the concrete slab, the weight of the wall and weight of water flowing in the channel. Due to the very weak rock, which consisted of mainly laterite, rock anchors were unable to be employed to resist buoyancy forces.

Figure 9. Condition of dam spillway outfall channel prior to remediation work.

The spillway channel chute slab was thickened with additional cut-offs provided to counter act the design uplift forces. The uplift was assumed to be 35% of the flow, following the recommendations of McLelan (1976) and Khatsuria (2004). Because of the varying width, depth and velocity, calculation of the buoyancy and velocity uplift forces was undertaken at every 2.5 m metres along the chute to determine the critical uplift forces and, hence, to size the thickness of the spillway channel slab. The slab thickness was determined to be in the range between 300 mm and 500 mm. It was also optimised in keeping with desired pour lengths and drop structure locations to allow for the reduction in slab thickness to reduce cost and improve constructability.

The typical arrangements for drop structures are shown in Figure 10. Further, in order to allow for effective drainage from beneath the concrete lining, drops in the slab at regular intervals have been allowed for. These also involve a typical 750 mm deep cut-off.

Due to the cut-offs, drop structures and the geometrical and shape (varying width) of the channel, the spillway channel chute was assumed to be fully restrained (Figure 11). Taking this restraint into account in the design through combining SFRC with one layer of N12 at 100 mm spacing custom-made steel mesh, enabled the construction of the floor without any joints for the entire 400 m length with a design nominal crack width of 0.20 mm. There were no limits on the time between adjacent slab pours or between the time that the floor had been poured and the walls being constructed. This solution was economically beneficial when compared to the conventional design which used 2 layers of N28-150 bars and the installation of expansion and control joints requiring dowels, waterstops and sealants.

In addition, the use of SFRC enhances the erosion resistance of the spillway channel chute. Some upstream faces of the spillway channel transitions may be subject to impacting flows while downstream faces may be subject to negative pressures and eddy currents.

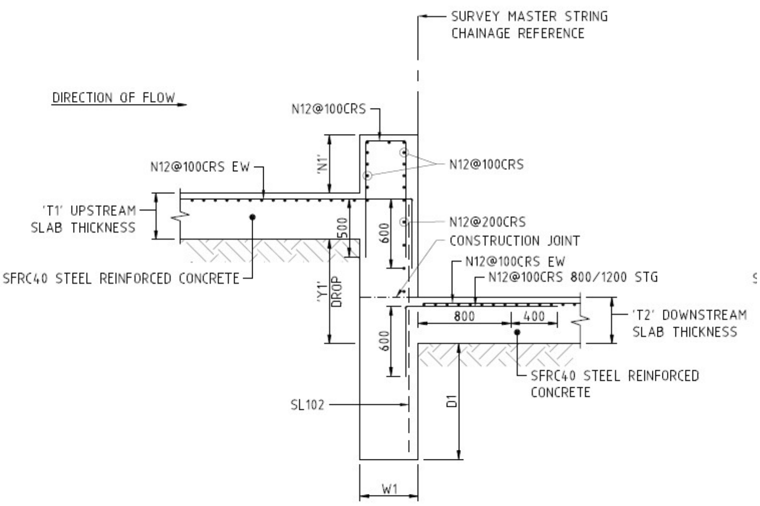


Figure 10. Typical drop structure and cut off.

Figure 11. SFRC combined with conventional reinforcing joint free Happy Valley Dam Outfall Channel, Australia.

Other case studies

Koprubasi Dam Spillway, Turkey

Constructed in 2008 for the Turkish General Directorate of State Hydraulic Works, this joint-free watertight spillway (Figure 12) is 500 mm thick and totally joint free. The conventional design used 2 layers of heavy reinforcing bars, closely spaced and was very expensive with a complex jointing system. In addition, the steepness of the spillway posed significant challenge in placing the heavy reinforcement and joints during construction. The SFRC option was adopted in combination with much lighter reinforcement, which resulted in a solution that was cost effective, joint free, more durable and quicker and easier to build.

Figure 12. SFRC combined with conventional reinforcing joint free Koprubasi Dam Spillway, Turkey

Longshou II (Xiliushui) Dam concrete face slab, China

While the primary focus of this paper is spillway design; a SFRC combined with conventional reinforcing joint free system was also adopted for the upstream face of the Longshou II Dam concrete slab. The dam is a 146.5 m high concrete faced rockfill dam, located in a high seismic zone. The valley is asymmetrical, with a width to height ratio of 1:1.3. The climate is extreme, with a wide range of temperature variation between day and night. Because of the unique topographical conditions, the face slab is subject to high tensile stresses. The original design with conventional reinforcement exhibited cracking to an unacceptable level during construction. Soon after this occurred, a SFRC combined with conventional reinforcing system was adopted for the top 75 m of the dam. The target of crack control was fully achieved. To-date, it is still performing extremely well even after experiencing at least two major earthquakes (Zhou and Zhang, 2005; Lu, 2008; Yang et al., 2008).

Figure 13. SFRC combined with conventional reinforcing system for Longshou II CFRD face slab, China.

Conclusion

Spillway structures play an essential role in regulating the design reservoir water level and are of paramount importance to protect the structural integrity of the dam structure. Concrete impermeability and tight crack control are of prime importance in the design and construction of the spillway lining in order to minimise the potential failure modes associated with cavitation damage and stagnation pressure related failure. In terms of good dam engineering practice, spillway chutes are generally constructed on well-prepared, clean but irregular rock surfaces and, more commonly, the chutes are also held down by ground anchors to resist the uplift and negative pressure. Detailing the chute to avoid cracking is complex as the chute is essentially continuously restrained by the roughness of the rock surface and the ground anchors. There is an upper limit on the chute panel size and shape. Heavily reinforced and of course watertight joints are required at close intervals, which are expensive, time-consuming to construct and require on-going maintenance. Even with all this effort, cracks can still occur, and when they do they can be large and wide enough to have an adverse effect on the performance of the spillway and, hence, put the dam at high risk of failure.

SFRC is recommended for resisting cavitation and erosion in accordance with the ICOLD Bulletin No. 40 and the Australian Standard AS 3735 Liquid Retaining Structures. Steel fibres combined with conventional reinforcement provides an amazing synergy to effectively reinforce concrete due to their ability to provide an effective restraining tensile force across any crack that opens and has enabled engineers to look outside the square. For the spillway chute, this means any concrete panel size or shape can be considered, even when the chute is fully restrained, and, most importantly, this cost effective solution can be constructed joint free while maintaining water tightness.

This allowed the entire 400 m long Happy Valley Dam Outfall Channel to be constructed joint free using the combined reinforcing solution. The solution was more cost effective, durable and quicker and easier to build than a conventional system using 2 layers of reinforcing bars with expansion and control joints. The SFRC combined with conventional reinforcing solution has also been applied to several major dam structures globally.

Acknowledgements

The authors would like to thank South Australian Water Corporation for allowing the Happy Valley Dam Outfall Channel to be shared with the wider dams community. They would also like to thank the broader SMEC, BOSFA and Bekaert design team and the Bardavcol construction team who have contributed to the success of the project.

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