Challenges and solutions for expansion joints on super long span bridges

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Summary

Exceptionally long bridges, designed and built by a construction industry that continues to push the boundaries of span and performance for such structures while at the same time always striving for greater cost-effectiveness, require carefully selected and detailed deck expansion joints. While it may be quickly concluded that joints of the modular type should be used, it is important to also be aware of the differences between the modular systems of different suppliers, and to entrust the design and manufacture of these key components only to a supplier that can demonstrate substantial experience in the specialised task of designing and manufacturing such components to satisfy the exceptionally demanding requirements of extraordinary bridges.

Keywords: Expansion joints; bridges; long spans; large movements; testing; durability; life-cycle

1. Introduction

The design and construction of super long span bridges, with main spans of over 3km currently being designed, presents particular challenges for their mechanical and moving parts, such as the expansion joints that provide a driving surface for traffic at the ends of each deck section while allowing the deck to expand, contract and move due to a variety of forces. Notably, the expansion joints in the bridge's deck face unprecedented demands due to the larger, faster and more complex movements and rotations that result. Such extreme conditions call for innovative design concepts, taking into account various aspects such as the development of new materials, prototype testing, durability under normal and exceptional service conditions, construction logistics and life-cycle cost. While a great deal of research and development effort is devoted to the general challenges of super long span bridges (including extensive wind tunnel testing, for example), little consideration is given to the corresponding challenges faced by expansion joints, perhaps due to their very specialised nature. This paper explores these challenges and comments on how they may be addressed.

2. The challenge

Even on bridges which do not have very long spans, expansion joints are often recognised as being particularly susceptible to damage and failure. For example, the 2003 report, "Bridge Deck Joint Performance - A Synthesis of Highway Practice" [1], published by the Transportation Research Board of the American National Research Council as Synthesis 319 of the National Cooperative Highway Research Program (NCHRP), stated very plainly: "Most bridges have deck joints, and most deck joints have problems". This simple statement indicates how often the design / fabrication / installation / maintenance chain has broken down during the lifetime of even small expansion joints, which make up the great majority of all expansion joints installed to date. Larger expansion joints, required by the relatively small number of long bridges constructed, face correspondingly greater challenges. In the case of very long span bridges (or super long span bridges, insofar as these already exist or are being planned), only exceptionally large expansion joints will satisfy requirements. Noting that such structures tend to be suspension bridges, an indication of the number in service, and thus of such large expansion joints, is provided by the national bridge inventory database of the Federal Highway Administration of the United States Department of Transportation [2]. The June 2011 version of this database records that of the 599,790 bridges in the United States at that time, just 96 were suspension bridges – or less than 1 in 6,000. This gives some idea of the specialised nature of the expansion joints needed for such structures - even those which would not be termed "super long span bridges". Some aspects of the challenge faced in their supply are described below.

2.1 Increased and increasingly complex movements

As bridge deck spans increase, the maximum movements which must be accommodated by the expansion joint at each end also increase, to the point where some structures already require joints which will accommodate longitudinal movements of over two metres. And as the deck is designed to be lighter, the secondary, frequent movements of the bridge also increase, as the effects of non-seasonal influences become more significant for the less robust structure. A light bridge deck will move more due to wind, traffic and short-term temperature changes (for example, as the sun goes behind a cloud) than a heavy one, with the result that the total accumulated movements which must be accommodated by its expansion joints increase greatly and can result in a modern slender bridge moving several hundred kilometres during the lifetime of its expansion joints.

Not only are the movements (both absolute and accumulative) of a long-span bridge likely to be considerably larger, they are also likely to be more complex. The relatively light, flexible deck of such a structure, and the relatively complex design of the structure as a whole, can give rise to rotations of the deck about every axis and movements in every direction, and these rotations and movements can be highly unpredictable. For example, bending of the deck structure of a bridge, caused by common forces such as traffic or wind, results in tension in its suspension or stay cables which in turn leads to movements of other parts of the deck and the bridge pylons. These movements of deck and pylons may individually translate to movements of the deck immediately to each side of the deck's expansion joints, but the movements are unlikely to be synchronised and so will display a high degree of randomness. They are also likely to be much faster and more erratic than those of a shorter-span bridge.

Measurements of the actual movements of the decks of long-span bridges indicate how movements can vary from one structure to another, and how extreme they can be in certain cases. The following measurements were made by the company of the authors, primarily using a *RoboControl* automated monitoring system of the type described in Section 5.3 below.

- Incheon Bridge, South Korea (12,300m-long bridge with 800m-long cable stayed main span): Accumulated sliding distance of 3.93 km per year, with 35,040 joint opening/closing cycles per year
- Run Yang Yangtze River Bridge (suspension bridge with 1,490m main span, see Figure 8): Accumulated sliding distance of 36.9 km per year, with 262,800 joint opening/closing cycles per year
- Lillebaelt Bridge, Denmark (suspension bridge with 600m main span): Accumulated sliding distance of 98.1 km per year.

2.2 Increasing traffic loading

At the same time as movement demands increase, traffic loading also continues to grow, presenting another challenge. If the expansion joints of a bridge are crossed by 30,000 vehicles per day (while some bridges carry much more), the total traffic volume during an assumed working life of 40 years or more will be likely to exceed one billion axle loads. This enormous figure indicates why fatigue is a major issue when designing durable expansion joints, especially when it is considered that each vehicle axle imparts not only downward vehicle weight forces but also horizontal forces due to traction, braking, turning and direction of travel, and that these forces are dynamic as opposed to static, with wheels impacting against the surface of the joint rather than applied gently to it. The effect of the dynamic nature of the loading is severe, as indicated by the dynamic amplification factor (DAF) which expresses the dynamic impact as a multiple of the static impact the same load would have. In fact, it is now believed to be more severe than was widely recognised in the past (when DAF values of 1.7 were commonly applied in the assessment of the performance of modular expansion joints), with testing by Ancich measuring a DAF of 4.6 [3]. And the impact on the durability of the joint is also severe; NCHRP Report 467 [4], for example, notes: “When the root cause of an overall failure is a failure of the structural supports (i.e., the centerbeams and the support bars), it is usually the result of fatigue cracking”. The design and fabrication of joints to accommodate this dynamic loading is thus critically important.

2.3 The demand for durability

The combination of such increasingly demanding movements and loads on the expansion joints of modern, long-span bridges requires suppliers to continue to improve the functionality and performance of their products. Not only must the joints of a large bridge satisfy all movement and loading demands, they should also offer excellent durability and reliability, enabling them to safely fulfil their vital function as long as might be reasonably expected of such relatively light, mechanical components, with the minimum of interruption for maintenance and repair. This demands careful consideration of the fatigue failures that can result from the relentless dynamic loading mentioned above, but also of other factors such as the bridge’s environment. Super long span bridges will almost certainly be built in coastal areas, posing a particular challenge for the durability of their expansion joints: corrosion. The harsh marine environment, with saline water and strong winds, is most detrimental to steel components which have not been designed to minimise contamination, fabricated from suitable materials and appropriately treated with corrosion protection. It must also be considered that such joints, even more than others in less harsh environments, will require re-application of corrosion protection (generally by painting) some time after the joint has been installed, so access to the susceptible parts of the joint should allow this work to be done well and without great difficulty.

By recognising and addressing the demand for durability, the total costs of a bridge’s expansion joints during the lifetime of the main structure can be minimised. These total costs include not only the direct costs of expansion joint supply, installation and maintenance, but also indirect costs and impacts such as those associated with traffic management and traffic congestion during repair or replacement works.

3. Addressing the challenge: selection of joint type

As noted by NCHRP Synthesis 319 [1], which ascertained and summarised the practices and preferences of the state and province transportation departments in the United States and Canada at the turn of the century: “For longer spans there are only two expansion joint choices: the finger joint or the modular system”. Finger joints (of the sliding variety needed for large movements) contain on their surfaces intertwining fingers from each side of the bridge gap, which are supported from beneath and pretensioned downwards in various ways, while modular expansion joints contain on their surfaces a number of lamella beams which divide the movement range at the end of a bridge deck into smaller individual gaps. Modular joints are relatively complex structures; the lamella beams on the surface are supported by perpendicularly orientated beams underneath, along which the lamella beams slide, and are connected with special sealing profiles to form a water-tight unit.

Although the choice of expansion joint type is so limited, when it comes to very long spans, or especially so-called super long spans, even finger joints may not present an option. These are relatively limited in the movements and rotations they can accommodate, and as noted above, long span bridges tend to have more slender decks which exhibit more complex, less predictable movement behaviour. Modular joints, on the other hand, can (depending on the supplier’s design) provide a high degree of flexibility, enabling the joint to also move transversely and vertically, and to rotate about any axis, as may well be required by long span bridges. So if significant transverse or vertical movements, or rotations about a bridge longitudinal or vertical axis may arise, a modular joint may be the only choice.

Even if a finger joint could accommodate all movements and rotations of a particular long-span bridge, further factors must be considered before choosing it over a modular joint - perhaps most significantly, the protection that the joint provides to the structure beneath. As stated by NCHRP Synthesis 319 [1]: “it is important to minimize the leakage to avoid serious damage to the bridge structural support system”. It goes on to note that finger joints, like other types of open joint (as opposed to closed joints such as the modular type) are not as widely trusted by the responsible agencies, as even the drainage troughs which can be provided are not always reliable. The same importance of preventing leakage through joints, and the same lack of trust in the drainage troughs of finger joints, is expressed by the AASHTO LRFD Bridge Design Specifications [5], which state: “Closed or waterproof deck joints should be provided where joints are located directly above structural members and bearings that would be adversely affected by debris accumulation. Where deicing chemicals are used on bridge decks, sealed or waterproofed joints should be provided ….. Given the unreliability of troughs, sealed expansion joints are a better option than finger joints fitted with troughs”.

Modular expansion joints thus very often represent the ideal choice of joint type for long span bridges. Indeed, the above referenced NCHRP Synthesis 319 [1] notes that the consensus among the agencies is that they are “the best of current alternatives for large movement bridge decks”. Of course finger type joints have a number of advantages which make them an ideal solution in many circumstances: they are not as complex as modular joints, and thus generally require less maintenance and replacement of components; they offer smooth, comfortable passage for vehicles and their occupants; and they are quiet under over-rolling traffic. But for very long span bridges, the argument for the selection of modular expansion joints in the majority of cases is very convincing. This is demonstrated in practice by the use of modular joints on very large bridges all around the world, including, for example, in South Korea, where modular joints with at least 15 gaps (allowing movements of up to 1,200mm) have been supplied by a single manufacturer for no fewer than four suspension and cable stayed bridges: the Kwang Ahn Bridge in 2002 (15 gaps), the Machang Bay Bridge in 2007 (18 gaps), the Geoga Bridge in 2009 (15 gaps) and the Incheon Grand Bridge, also in 2009 (24 gaps).

In practice, the choice will very often come down to the personal preference of the bridge designer or owner, which of course is strongly influenced by his or her experience with different types of expansion joint in the past and by preconceptions about the relative strengths and weaknesses of each variety. Such a basis is therefore highly subjective, so the input of a suitably experienced advisor can be of great value. Very often the best advice can be provided by an expansion joint supplier who offers both types and so can comment on the advantages, disadvantages and implications of the use of different joint types in any particular situation.

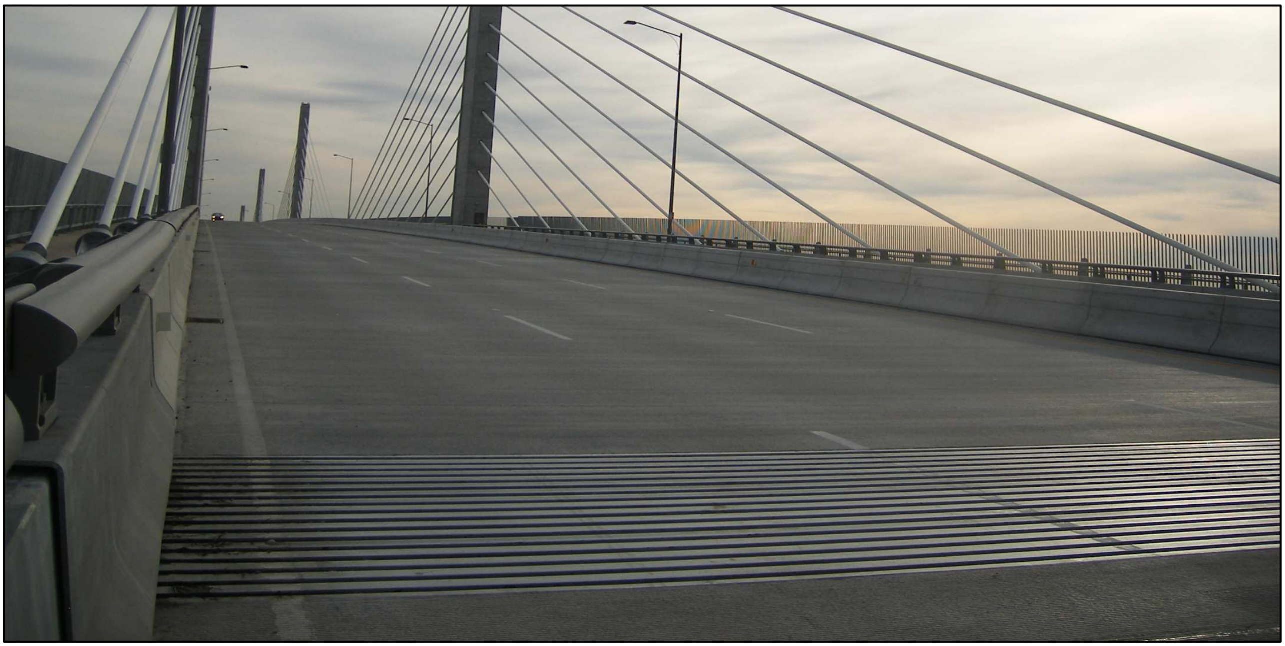

Fig. 1: The Golden Ears Bridge in Canada – equipped with 17-gap modular joints with Fuse-Box (refer Section 4.5 below)

4. Addressing the challenge with modular joints

As noted above, modular expansion joints (as shown in Figure 1) have a great deal to offer the designers and constructors of large bridges, thanks to their ability to facilitate very large longitudinal movements and (depending on their design) their great flexibility - no other type of joint can accommodate longitudinal movements of two metres or more while also facilitating movements in all directions and rotations about all axes. The design of the joint of one supplier, and its flexibility, is illustrated in Figures 2 and 3 below.

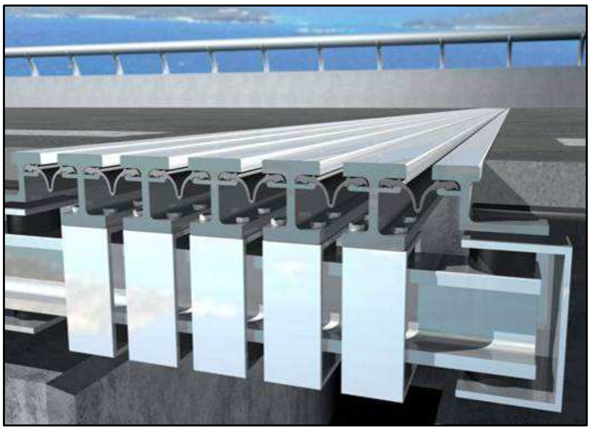

Fig. 2: Schematic section of a modular joint, showing its construction

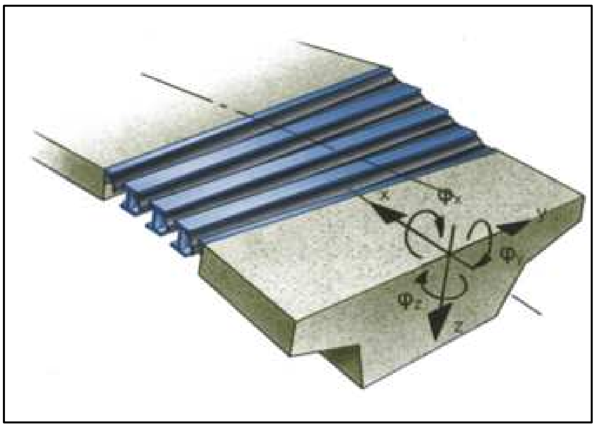

Fig. 3: The exceptional flexibility of some modular joints – with 6 degrees of freedom

Such joints are complex, highly engineered components, and are far lighter and therefore more susceptible to damage and wear than the main bridge structure – especially in the case of the sliding surfaces and elastomeric components which make possible the exceptional movement capacity and flexibility of the joint. So although modular joints may often present the best (or only) option for long span bridges, they face a number of particular challenges which increase in line with the magnitude and complexity of the deck movements they must accommodate. These include the need for features such as those described below.

4.1 Special sliding materials

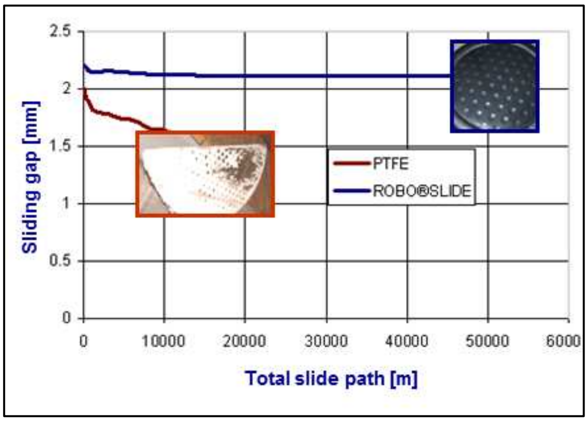

Fig. 4: Comparison of resistance to wear of the sliding materials PTFE and RoboSlide

The sliding material normally used to facilitate the sliding of the moving parts of an expansion joint could not withstand the extreme movements of the expansion joints of super long bridges, and a suitable alternative must be specified. A material which satisfies such demands is, for instance, *RoboSlide*. This is a high grade sliding material with excellent abrasion resistance and very low friction characteristics. Tests carried out on this material showed that above a sliding distance of 2.5km, the friction level is approximately 5 times lower than that of PTFE for this application. The material has also been shown to be twenty times more durable (see Figure 4) and 2.5 times stronger in compression.

4.2 Asymmetrical, elastic control system

Control systems are used in modular expansion joints to regulate the widths of the gaps between the joint's lamella beams, and these may be elastic or rigid, depending on manufacturer. The elastic variety consists of pairs of elastomeric springs, connected by steel plates, which couple lamella beams together, and offers several advantages over the rigid type (especially considering the movement demands of long span bridges as described above): It provides damping and intermediate supports to the lamella beams, offers increased flexibility, is not susceptible to slip-stick movements, and is forgiving of the constraint effects that might result from gap blockages. However, the normal symmetrical arrangement of the control spring pairs does not suffice when the movement capacity becomes very large, due to the friction forces which arise as the joint opens and closes. To overcome this problem, and ensure that the movement of the joint will be evenly distributed among the joint's gaps, an asymmetrical control system may be used. This incorporates a staggered layout of the control springs, with the number of springs being increased at one end of the joint to counteract the build-up of friction forces at the other end. Figure 5 shows the underside of a joint with such a system.

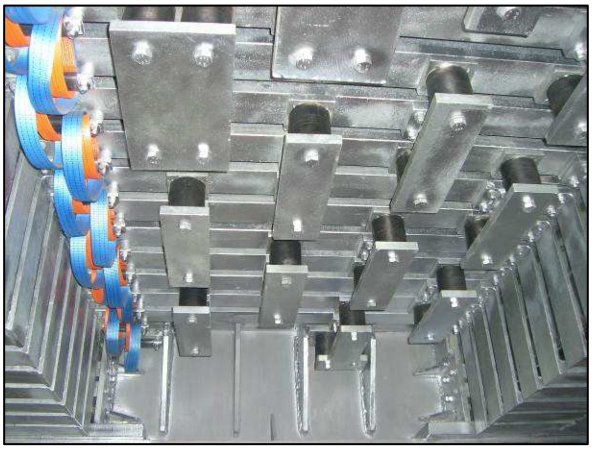

Fig. 5: Underside of a large modular joint with asymmetrical elastic control system

4.3 Advanced bearing-spring system for damping

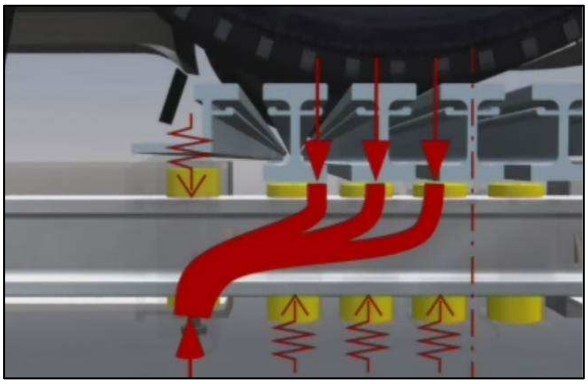

Fig. 6: Advanced bearing-spring support

Similar to the control systems mentioned above, the supports and connections of the key structural members of a modular joint may be rigid or elastic, again depending on manufacturer. Again, the elastic variety (such as the sliding bearing and sliding spring pairings shown in Figure 6) offers advantages, in particular for long span bridges. Such a system provides damping of the dynamic traffic loading which as noted above can otherwise have a severe impact on the joint, and safely transfers it to the bridge structure, protecting both the expansion joint and the bridge from fatigue failure.

4.4 Anti-skid surfacing

Fig. 7: Anti-skid surfacing on the driving surface of a modular joint's lamella beam

As the span of a modular expansion joint increases, so too does the distance a vehicle will have to travel in crossing its steel surface with reduced ability to brake, especially in wet conditions. Large expansion joints therefore require some form of surface treatment to improve tyre grip. An example of a proven anti-skid surface is shown in Figure 7 - a five-layer laminate coating that is applied cold in liquid resin form and offers a friction coefficient of up to 0.9, and excellent durability.

4.5 Seismic design feature

An interesting possibility may arise in the case of long span bridges which must accommodate seismic movements. Since bridge design requirements often allow a certain amount of damage in the case of an earthquake, a modular joint which makes use of this allowance may offer an attractive alternative to a regular joint. As described by Spuler et al [6], such an approach, using the so-called *Fuse-Box* feature, was implemented in the construction of the Golden Ears Bridge, Canada in 2009 (see Figure 1). The *Fuse-Box* allows the expansion joint, during an earthquake, to break free from the bridge deck in a controlled, designed manner, without serious damage to itself or the deck, and to be reconnected without difficulty. Thanks to the approach taken, the number of gaps in the joints could be reduced, allowing the cost of the joints to be optimised.

5. Life-cycle considerations

No solution to a challenge such as that described above is complete without consideration of life-cycle issues. This is discussed in some detail by Spuler et al [7], but some considerations with particular relevance for super long span bridges are discussed below.

5.1 Interaction with other mechanical and moving parts

Very long span bridges will almost certainly be of the suspension or cable stayed type, and thus rely on cables to support the deck. Their decks will also be designed to be as light as possible, to reduce the weight on the cables and of course the cost of construction. And as noted above, the deck movements are likely to be large and erratic. Therefore, in addition to the expansion joints and cables, the bridge design is likely to incorporate bearings with exceptional movement or loading requirements, and dampers or seismic protection features. These key components act together to facilitate and control the movements of the bridge's flexible deck and the forces they generate, and thus impact on each other in various ways. For instance, the forces which arise in suspension cables may cause the deck at an expansion joint to move and rotate, with obvious implications for the joint and the bearings beneath which support the deck – but the movements and rotations, which may otherwise be very fast and erratic, can be controlled and damped by the use of hydraulic dampers, greatly reducing the wear and tear on the joints and bearings and extending their life. Or the opening/closing movements of a bridge deck may introduce large vertical movements at an expansion joint if the sliding surfaces of its bearings are not parallel to the deck surface.

This interrelationship between these various mechanical components, and the fact that all require in-depth knowledge of the same aspect of bridge design and behaviour, has the logical consequence that some suppliers specialise in several or all of them. This enables them to develop and design solutions which optimally address the bridge designer's overall challenge, and to provide valuable support to bridge designers in their work.

5.2 Verification of performance

Long span bridges are built at enormous cost, which can only be justified by the great importance attributed to the structure and the purpose it will serve in transporting traffic. Therefore, closures of the structure to traffic for repair or replacement of its expansion joints must be kept to an absolute minimum. It is thus vital that the performance in service of a particular expansion joint is verified in advance of its selection for use. This can be done by laboratory testing – for example, of fatigue performance, daily opening movements, vibrations from traffic, seal strength or performance in an earthquake, as described by Spuler et al [8]. However, it must be recognised that the degree to which laboratory testing can replicate actual service conditions is limited by the need to make testing practical and affordable. This dictates that any particular test can only assess certain defined performance characteristics, and that such testing will be based on various simplifications and assumptions. But no combination of practical, affordable laboratory tests can accurately assimilate the full range of demands experienced by a joint in service. Therefore, the best testing of an expansion joint for use on a long span structure is actual service on other long span structures which will place similar demands on the joint. A strong track record on the part of the expansion joint supplier, with evidence of satisfactory performance on many comparable structures over many years, is arguably far more relevant than successful completion of defined laboratory testing.

5.3 The potential contribution of automated monitoring systems

The ongoing drive to build larger, longer and ever more economically results in bridges today being built in ways which are pushing ever further the boundaries of what is believed to be possible or practical. This means that bridges are often built to innovative designs, and using materials and construction methods, which have not been proven in practice. This can leave an element of uncertainty about the reliability of a proposed solution, which may result in a perfectly good approach being rejected. A solution to such a situation is offered by automated monitoring systems, which can provide detailed, real-time information on the condition and performance of any structure or structural element, enabling a bridge designer or constructor to have confidence that the structure is performing as intended, and that any unexpected changes in its performance will be immediately recognised, greatly reducing the potential consequences of any residual risks [9].

6. Conclusions

Exceptional structures require exceptional key components, and super long span bridges require extraordinary expansion joints. Modular joints are likely to provide the optimal solution in the majority of cases, but designs vary from one supplier to another, so the precise characteristics of the modular joints available must be carefully assessed for suitability. The design and manufacture of such exceptional joints is a highly specialised task, and should only be entrusted to a supplier that can demonstrate a strong track record in the supply of similar joints for comparable structures. Armed with a tried-and-tested design and proven manufacturing capabilities, and with detailed knowledge of joint design possibilities and the interrelationship between a bridge's expansion joints and its other key components, such a supplier can optimise the design of the joints and provide valuable support to the bridge designer in determining how the critical mechanical parts of the structure interact, resulting in an improved life-cycle performance of the structure as a whole.

Fig. 8: The Run Yang Yangtze River Bridge in China, with its 1,490m main span – equipped with 27-gap modular joints since constructed in 2004 (world record joints at the time)

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