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Potentially-innovative options in designing suspension bridges with railway crossing

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Abstract. Both the first author and the company of the second author were involved, directly or indirectly, in the design stage of a permanent link between the bottom of the Italian peninsula and the nearby Sicily island. This ambitious project was left in stand-by from 2013 to 2023. The current political revival originates some thoughts on the updated desired performance of suspension bridges, without any immediate reference to that specific crossing. It is simply regarded as a starting point. After an update on recent worldwide realizations, the authors focus their attention on four basic aspects: the span length, the girder scheme, the foundation technology and the bridge runability. Eventually, structural control and monitoring aspects are discussed as potentially innovative options in designing suspension bridges with railway crossing.

Keywords: bridge runability; foundations; girder scheme; span length; suspension bridges

1. Introduction

Technical choices along the design of large-scale infrastructures, and/or their structural components, have to deal with constraints resulting from social and political issues. The standard pursuing of structural safety, robustness and resilience by the minimal economic effort is no longer an exhaustive policy and has to be extended to incorporate environment considerations, sustainability and social impact.

A report, celebrating the two decades since the re-starting of the official technical activity for the Messina Strait Bridge, after the first political revival in 2002, appeared recently on the Italian online website “Ingenio” (Bontempi 2022). The reader can catch, along the report, the fervent activity that led the company in charge to prepare the tender documents, the tender itself and the award of tender. More details were also synthesized in the book edited by Calzona (2008). The title of this book is a direct reference to the translation in Italian of the Popper’s autobiography “Unended Quest”.

The tale mainly developed in the period 2004-2006, to reach an apparently definitive political stop in 2013. The year 2023 sees a second political revival. Who, like the first author or the company of the second author, directly participated in this activity (as well as, in the Nineties, in the studies promoted toward a floating tunnel link) had to sign a confidentiality agreement. The rights owner explicitly authorized a few dissemination bits (Casciati 2006a, b). This makes one suspicious on the current journalistic shooting, semi-technical conferences and parliamentary hearings, since of the two one is true: either the contributor is violating the confidentiality agreement or does not possess the necessary documentation on the bridge features.

Outside the Italian borders, several bridges of very long span have seen their design and construction in the last decade. The consequent potential fall-out toward an update of the current design for the Messina Strait Bridge seems to be proud of discussion. With this purpose, after a brief presentation of what is new in the specific field, four main aspects are first discussed: the span length, the girder scheme, the foundation technology and the bridge runability. Eventually, structural control and monitoring close the screening of options for a potential innovation in the design process of suspension bridges with railway crossing.

2. One decade of recent long span bridges

Long span suspension bridges, as well as long span cable-stayed bridges, are fascinating the public opinion and, hence, prone to generate a significant dissemination activity. As a result, the reader can find the details of several infrastructural works directly in Wikipedia, so that specific references are not strictly required. In detail:

- The Bridge of Russkij Island has seen its inauguration on September 3, 2012. It is a cable-stayed bridge of main span of 1104 m over a total bridge length of 3100 m. The bridge serves vehicular traffic only, over a width of 29.5 m. The cost was estimated at one billion US dollars. With reference to

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Table 1 The ten longest suspension bridges in 2018 (re-elaborated from (Ge *et al.* 2018))

No.	Bridge	Main span [m]	Girder	Wind-induced problems	Control method	Location	Year
1	Akashi Kaikyo Bridge	1991	Truss	Flutter	Slotting/stabilizer	Japan	1998
2	Xihoumen Bridge	1650	Box	Flutter	Central slot	China	2009
3	Great Belt Bridge	1624	Box	Vortex-induced vibration	Guided vane	Denmark	1998
4	Osman Gazi Bridge	1550	Box	-	-	Turkey	2016
5	Yi Sin-sun Bridge	1545	Box	Flutter	Central slot	Korea	2012
6	Runyang Bridge	1490	Box	Flutter	Central stabilizer	China	2005
7	Nanjing 4th Yangtze Bridge	1418	Box	Vortex-induced vibration	Guided vane	China	2012
8	Humber Bridge	1410	Box	-	-	UK	1981
9	Yavuz Sultan Selim Bridge	1408	Box	-	-	Turkey	2016
10	Jiangyin Bridge	1385	Box	-	-	China	1999

the entire length, a cost of 11,000 US dollars per square meter is obtained. A specific French technology is evident in the design. The antenna height is 320.9 m.

- The third bridge over the Bosphorus (Yavuz Sultan Selim) was inaugurated on 26-08-2016. It is a suspension bridge with a total length of 2164 m and a main span of 1408 m, which houses eight motorway lanes to which two railway tracks could be added in its 59 m width. Its works started on 29-05-2013. The Washington Post of August 27, 2016 reports the cost of 3 billion US dollars. Using the total deck area, this amount results in a cost per square meter of US$23,000. The designer has been the French Michel Virlogeux, who had also designed the cable-stayed bridge of Millau, which inspired the bridge of the island of Russkij. The antenna height is 322 m.

According to the competent website www.partnershipbordersstudy.com, the cost per square meter of a suspension bridge should fall in the range of 8000/9000 US Dollars. It is worth noticing, however, that the cost of a bridge is often provided without specifying whether it concerns only the maximum span segment or covers the entire extension of the bridge.

A part from the above inaugurations that had received acknowledgment in the news, what attracts the collective imagination is the fervent activity in mainland China. Not that the two recent constructions mentioned above were devoid of them, but entering this country one cannot ignore the political significance that the Chinese government associates with the construction of civil infrastructures. Almost in a Guinness Book of Records challenge, emphasis is put on what has been achieved in terms of length of the connections or orographic height of the connections. See Appendix A for details in this context.

A group of Chinese scientists (Ge *et al.* 2018) published a table of the longest suspension bridges from where Table 1 is re-elaborated. Differently from the response of standard media (as Wikipedia or Google, which only provide a list of bridges ranked by the length of their spans), this table adds some bits of information, outlined by colored frames, useful in view of the discussion in Sections 4 and 6. The availability of this table allows the authors to successfully consult the literature review (Huang *et al.* 2020) where emphasis is put on the suspension bridges in China whose span is among the ten longest in the world:

1. the Nansha Bridge, with a span of 1688 m, height of 211m and completed in 2019 is listed as second after the Akashi bridge, completed in 1999, with span 1991 m, for 3991 m of total length, and height 282.8 m. It enters the ranking in second place instead of
2. the Xihoumen Bridge, span 1650 m., height 211 m and completed in 2009. The other mentioned bridges are scaled down one position with respect to Table 1; namely,
3. in seventh place the Runyang Yangtze River Bridge, 1490 m., height 215 m. and completed in 2005;
4. in eighth place the Dongting Lake Bridge, 1480 m., height 206 m. and completed in 2018;
5. in ninth place the Fourth Nanjing Yangtze River Bridge, 1418 m., height 229 m. and completed in 2012.

All these bridges are devoted to the vehicular traffic only.

Indeed, in March 2022, the new vehicular suspension bridge over the Dardanelles was inaugurated with a span of 2023 m and height 334 m., which exceeds the 1999 m of the Akashi Bridge that was the longest at the time of drafting the article mentioned above. The Daradanelles bridge covers 4608 m with a width of 45 and a cost of 2.7 billion US Dollars. One gets 13020 US Dollars per square meter. The Danish company COWI played an important role in the design, as well as in that of the Osman Gazi Bridge, with a maximum span of 1550 m and height 234.425 m,also in Turkey.

In October 2019, the longest vehicular suspension bridge in China, the Yangsigang Yangtze River Bridge, was inaugurated with a span of 1700 m. and height 254.9 m., part of a link costing 1.27 billion US dollars with a length of 4134 m. Estimated cost per square meter 6150 US dollars if the declared cost referred to the entire connection or 15,000 US dollars per square meter if referred only to the suspended section.

The paper (Huang *et al.* 2020) also lists the Wufengshan Yangtze River Bridge (6409 m long and 1092 m span, height 203 m., for a deck width of 40.5 m., opened in December 2020; Fig. 1). The cost of 0.97 billion US dollars

Fig. 1 Wufengshan Yangtze River Bridge

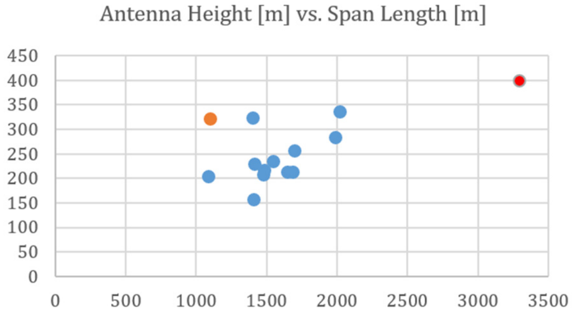

Fig. 2 Antenna heights vs. span lengths

gives 3732 or 20657 US$ per square meter, depending on the actual length one accounts for.

Fig. 2 provides a synthesis of the couples (span length, height) above reported, with the addition of that of the Humber Bridge, located in UK, with 1410 m. of span length and 155.5 m. of height. It was inaugurated in 1981 and serves vehicular traffic only. It is worth noticing that, since the Humber Bridge, its designer was participating in most of the Western realizations. Indeed, Wikipedia reports that William Brown (1928-2005) was the designer of an impressive sequence of designs actually realized:

- 1981- Humber Bridge, England, 1981, length 2220 m, span 1410 m (designed by Freeman Fox & Partners)
- 1988. Fatih Sultan Mehmet Bridge, Turkey, length 1090 m, span 1090 m (William Brown was the bridge designer and construction manager)
- 1998 - Great Belt Bridge, Denmark, 1998, length 6800 m, span 1624 m (the cable tension control method developed by William Brown was used)
- 2001 - Triangle Link, Norway, 2001, length 1077 m, span 677 m (Brown Beech built the suspension structure of the bridges).

The Messina Strait Bridge (span 3300 m, height 399 m) was designed in 1993, but it is still reported as in construction in Table 2.

In Fig. 2, the spurious Russian cable-stayed bridge is marked in brown. The couple of data for the Messina Strait Bridge, as for its current design, is represented by a dot in red.

3. Suspension bridges with railway crossing

If the field is now restricted to the bridges with railway crossing, Table 2, elaborated from (Zhang *et al*. 2015), can result useful. The authors of this paper reached Hong Kong from the airport by train crossing the Tsing Ma Bridge. They have seen with their eyes the train to cross the bridge in Lisbon, Portugal. At their knowledge, the 3rd Bosporus Bridge has not yet activated the planned railway link. By contrast the Wufengshan Yangtze River Bridge, carrying the Lianyungang–Zhenjiang high-speed railway and the Jiangyi Expressway [zh] over the Yangtze, was inaugurated on December 11, 2020. It is currently the world's longest span high-speed railway bridge, tied with the cable-stayed Hutong Yangtze River Bridget. All the three mentioned bridges carry the train tracks on a level below the upper deck. Actually the Minami Bisan-Seto Bridge, listed in Table 2, comes with the lower deck

Table 2 Chronology of the suspension bridges with railways (elaborated from (Zhang *et al*. 2015), modifications in red colour)

Bridge	Span /m	Railway/Highway	Open Year
Washington Bridge, USA	1067	4/8	1931
San Fransisco Bay Bridge, USA	705	2/6	1936
Naruto Bridge, Japan	876	2/6	1985
Shimotsui-Seto Bridge, Japan	940	4/4	1987
Minami Bisan-Seto Bridge, Japan	1100	4/4	1988
Kita Bisan-Seto Bridge, Japan	990	4/4	1988
Tsing Ma Bridge, China	1377	2/6	1997
April 25th Bridge, Portugal	1013	2/6	1999
Bosporus 3rd Bridge, Turkey	1408	2/6	2016
Messina Strait Bridge, Italy	3300	2/8	Under construction
Wufengshan Bridge, China	1036	2/8	2020

designed to accommodate an additional set of Shinkansen tracks for a proposed extension of the Shinkansen to Shikoku (Ohashi *et al.* 1988).

Some papers provide further details on the Wufengshan Yangtze River Bridge, namely Qin and Gao (2017), Zhao *et al.* (2022) and Wu *et al.* (2022).

The conclusion of previous section was that a suspension bridge of span 3300 m. would results 1.5 times longer than the currently longest bridge. The conclusion of this section is that the addition of high-speed train crossing would result in a span 3 times longer than the currently longest bridge.

Section 6 will discuss the matters related to structural control and monitoring. It is worth noticing, however, that the availability of three years of records of the sensor mounted on the Wufengshan Yangtze River Bridge represents an impressive database that should not be ignored in the design stage of a bridge in construction serving a high speed train line.

So far, the authors of this paper only used bits of information in the public domain. Documents, often titled “Design Rules and Performance Requirements”, are in the Western market private, confidential agreements between the owner and the triplet designer, builder, tester. Indeed, long span bridges go beyond the prescriptions of the ordinary national technical standards. The Japanese standard (Japan Road Association 2019) writes explicitly “The Specifications for Highway Bridges shall be applied to the design and construction of a bridge with a span length of 200 m or less. For a bridge exceeding 200 m in span length, the Specification can be applied with necessary and appropriate modifications according to the type, structure, site conditions, etc. of the bridge”. In synthesis, specifications for long span bridges are a task of the pool in charge of the ownership, planning, design and construction.

However, in China, where government funding is impressively repetitive, the document Specifications for Design of Highway Suspension Bridge (JTG-T D65-05-2015) has been drafted. As the title says, it only covers highway bridges. Railway bridges, and in particular for the crossing of high-speed trains, are a next step.

The aforementioned (Qin and Gao 2017) comments on the situation with these words:

“• The development of high-speed train bridges in China is still at an early stage and a significant effort is expected, also on an experimental basis, as support for the drafting of the related technical standards.

• Despite advanced research in Europe, Japan and Korea for the design of suspension bridges of spans of 2700–3300 m, the span of existing or under construction long span bridges is just over 2000 m.

• There is no extensive construction experience for bridges in an aggressive marine environment.

• For the future, research is oriented towards the development of new materials with high resistance, lightness and durability.”

4. Performance requirements

When significant financial investments are required, the point of view of economic experts becomes more and more predominant. There are several ideas in the literature, but what is striking is what was published in the Oxford Review of Economic Policy (Ansar *et al* 2016).

The article starts with some questions.

• “Is China’s economic growth a consequence of infrastructure investments over the past thirty years?

• Is China’s ability to design and build infrastructure a phenomenon that wealthy (Western) democracies can learn from?”

After arguing on the possible answers, the conclusions are a warning message: investing in unproductive projects initially results in a "boom" when construction is underway, but when the expected benefits do not materialize, these same projects become a dangerous drug for the economy.

These conclusions are the motivation of the wide-ranging researches underway in the main Chinese universities, including those of Honk Kong and Macau, which cover the monitoring of the currently operational high-span bridges. Control systems and built-in intelligence characterize the long-term programs. Section 6 is devoted to such developments. The present section and next section, cover the standard design process.

In the scientific literature one finds that the first paper reporting the aerodynamic aspects, of the 3300 m span bridge, dates back to 1993 (Brancaleoni and Diana 1993). However, the “Design Rules and Performance Requirements” were built ad hoc for the Messina Strait Bridge just twenty years ago (see Casciati and Faravelli 2007).

The span length was already deeply outlined in this paper. A joint look at Tables 1 and 2 clarifies where the scientific knowledge is, independently of desirable leaps forward.

The fourth column in Table 1 (that framed in bleu), shows that the longest bridge at the end of last century was conceived as a truss structure. This point will be resumed in next section when discussing structural control potential. All the other bridges have a girder box scheme, following the trend started with the Humber Bridge. This solution is prone to aerodynamics effects (as the sad experience of the failure of Tacoma Strait Bridge taught). The countermeasures (Yang *et al.* 2020) will be addressed in section 6, together with the different realization formats for the girder box section as driven by flutter considerations. In term of geometry, there is only one further new to mention: the introduction of non-vertical hangers during the construction (i.e., not in the design stage) in the Third Bosporus Bridge (Farooq 2017). This solution, which leads the designers to claim for a hybrid scheme of the bridge, was already investigated for applications to different bridges, but at that time, without outlining special advantages.

Coming back to the performance requirements, uncovered, or unsatisfactorily covered, items can be summarized in:

1. lack of resilience investigation. Twenty years ago all comes in addition to safety was regarded as robustness, i.e., the ability to prevent from large catastrophic events as originated by minor local damages. The ability to recover from a state where the serviceability conditions are lost was not discussed (Tateishi 2022).
2. lack of insight into the geometrical asymmetry, with consequent lacking balance of the forces transferred by the cable on the single pier. This situation directly comes from the constraint of having the pier foundations out of the sea, due to the existing technological limitations at that time.

With reference to the latter item, three recent achievements in mainland China are quite remarkable.

i. The foundation of the main tower of Sutong Yangtze River Bridge (Zhang *et al*. 2009) is the largest group pile foundation in the world. The group pile foundation is composed of more than hundred bored piles with a diameter of 2.8 or 2.5 m and length of 117 m, arranged in a plum shape. The bearing cap is in dumbbell shape, 113 m in length, and 48 m in width, and the thickness increases from 5 m at the edge to 13 m in the middle. Special attention was paid on reducing the ship impact.
ii. In the 1960s, when the Nanjing Yangtze River Bridge was built in China, heavy-duty concrete caisson, deep-water floating reinforced concrete caisson, and steel caisson were developed, which realized the application of caisson for the deep-water bridge foundation. The caisson foundation of the tower pier in the Taizhou Yangtze River Highway Bridge is the foundation sank into the soil with the largest depth in the world. The foundation adopts a rounded rectangular caisson with a section size of 58 m × 44 m and a total height of 76 m. The lower part is a steel shell concrete caisson, divided into 7 sections.
iii. Another case of caisson implementation is the Hutong Yangtze River Bridge, which also adopts a rounded rectangular sinking foundation with dimensions of 86.9 m × 58.7 m × 115 m, which is the largest caisson foundation in the world. The steel caisson adopts a double-walled compartment structure, which can fully utilize the buoyance of the water during the sinking and adjust the position of the caisson by changing the water level in the compartment (Huang *et al*. 2020).

5. Designing suspension bridges with railways crossing

Recently published literature (Su *et al* 2018, Cai *et al*. 2023) confirms that the train is still accounted in the bridge design as a moving live load, where dynamic effects are demanded to some amplification factors. Thus, the main parameter is the train speed, Separate analyses are devoted to the braking phase, where the design variables are the wheel-rail adhesion coefficient and the length of braking loads. The policy in China is that of having common rules of design (Li and Dai 2010). In Europe the document prepared by the Technical Committee CEN/TC250 (Technical Committee 2021), still to be approved by the organization, comes with clear rules on the need of a dynamic analysis, but leaves the trains definition to the owner of the infrastructure under design. This results, once more, in a predominant role of the Design Rules and Performance Requirement document specific for any single bridge. Apart from the actions above discussed, this specidic document is also fundamental in assigning the expected performance, as discussed in the remaining of this section.

The next issue, indeed, is runabilty. The vertical slopes related to the global deformation of the bridge deck and the lateral slopes of the bridge deck due to track eccentricities and irregularities should be limited to ensure train runability. The expertise collected two decades ago was mainly theoretical and numerical (Xia *et al*. 2000) without experimental validation. The research group that authored the paper (Zhai *et al*. 2013) introduced a framework for the systematic investigation of the high-speed train–track–bridge dynamic interactions. The purpose was provide a method (then implemented in a software) for analyzing and assessing the running safety and the ride comfort of trains passing through bridges. The vehicle-bridge coupled system must be solved with an iterative procedure, which is not unconditionally convergent. Based on it, (Zhang *et al*. 2015) developed an iterative scheme.

(1) Solve the vehicle subsystem equations under the following assumptions: the bridge subsystem is rigid, the bridge motion is null, the wind load is on the car-body. Moreover, one adopts the track irregularities as the excitation, to obtain the time histories of wheel-rail forces and moments for all wheel-sets;

(2) Solve the bridge subsystem equations by applying the wheel-rail interaction force histories obtained in the previous step combined with the wind load on the bridge deck to obtain the updated time histories of bridge deck motion.

(3) Solve the vehicle subsystem equations by combining the updated bridge deck movements obtained in Step 2 with the updated track irregularity excitations to obtain the updated time histories of wheel-rail forces and moments for all wheel-sets under the wind load.

(4) The convergence errors of wheel-rail interaction force histories are calculated. If convergence is obtained, the calculation is complete. Otherwise, the current results are used in Step 2 and another iteration has to be carried out.

A recent review paper also illustrates some validation tests (Zhai *et al*. 2019). A DIN document is also worth of mentioning (German Institute of Standardization 2014), even if no long span bridges with railway crossing were built in Germany.

Table 3 Structural monitoring instrumentation for some suspension bridges in mainland China. (re-elaborated from (Li *et al.* 2015)). The third bridge is mentioned in Table 1 as Runyang Bridge

Name of the bridge	**Tab. 1**	**Year**	**Number sensors**	**Data used for assessing**
Xihoumen Bridge	2	2009	341	Wind, traffic load, cable f. Deflection, strain, vibration
Nanjing 4th Yangtze R. Bridge	7	2012	188	Wind, traffic load, cable f. Deflection, strain, vibration
Zhenjiang-Yangzhou Yangtze R. Bridge	6	2005	214	Cable f., temperature field Strain, vibration
Jiangyin Bridge	9	1999	106+1680 optic fib.	Wind, cable force, humidity Temperature, vibration
Taizhou Yangtze R.	-	2012	274	Wind,temperature, humidity Displacem., strain, vibration

6. Potentially-innovative options

This section is devoted to structural control and monitoring, regarded as potentially innovative options in the design process. They are actually those of highest relevance in the context of this journal (Rahbari *et al.* 2015, Li *et al.* 2017, Mao *et al.* 2017, Meng *et al.* 2019, Fan *et al.* 2023). Structural monitoring has a twofold targets. Collecting data on the actual bridge performance is made in view of a prognosis, in its meaning of a forecast of the likely outcome of a situation. The same data are the necessary feedback for any structural control implementation different from those of passive nature. Structural control is to introduce in the design a margin of adaptability: if something is not behaving as assumed in the design process there is the chance of counteractions made possible by the installed active or semiactive control devices.

The authors address first the topic of structural monitoring. Two decades ago, attention was mainly focused on the environment monitoring without specific regulations on the targets of the structural monitoring campaign during the bridge lifetime.

Going directly to suspension bridges, the suggested reference, among others, is (Li *et al.* 2015), from which Table 3 was re-elaborated. Compare now the information in this table with that described in the papers (Ostenfeld 2004, Kitagawa 2004 and Wong 2004) covering the three main suspension bridges built in the last decade of last millennium. There is a large evidence that in two decades the topic went across a quite significant upgrade. One is expecting now the accessibility to the Wufengshan Bridge data toward a validation of the results of the most refined numerical model to study the runability.

One has to notice, however, the different level of confidentiality imposed in Western countries and in mainland China. In the former case there is an owner/manager of the infrastructure who prevents from the dissemination of the collected data. In mainland China, scientists have access to the data and are allowed to publish elaborations from them. This dissemination of collected data should be regarded as the basis for the refinements on the load numerical models up to now used in the analyses carried out in the design stage. This is especially true for the high speed train crossing.

The reader is addressed to Wang *et al.* (2022) for the innovative sensing technologies in this field.

The other topic to be approached, when dealing with smart structures and systems, is structural control. The bridges in the Western countries mainly mount bumper in the transversal direction between deck and pier. The due attention is paid to the extension joints that represent a critical aspect in suspension bridge design.

The columns, framed in green and in red in Table 1, provide the wind-induced problems and the control countermeasures, respectively. (Tanaka *et al.* 1998) comes with a discussion that help to introduce the problem. The Akashi-Kaikyo Bridge, as built, shows a central slot (open grating) between the two traffic lanes and a vertical stabilizer in the center top of the deck global section. The center slot in the middle of the deck plays a significant role for the improvement of the aerodynamic stability. The paper proposed the application of vertical and horizontal stabilizer to a tapered box girder that was never adopted. Passive aerodynamic countermeasures toward the flutter control scheme of super long-span bridges were reported in (Yang *et al.* 2020). Vertical stabilizers are still the subject of recent papers as (Zhou *et al.* 2023a).

When problems come from vortex-induced vibration, a guide vanes scheme is adopted in Table 1. Guide vanes can be regarded as composed of bent plates running along the bottom plate/lower side panel joints. Developments can be found in more recent publications as (Larsen *et al.* 2000) and/or (Zhou *et al.* 2023b).

In addition to those listed in Table 1, there are other bridge components that could find useful the adoption of a control scheme. For instance, the performance of multiple tuned mass dampers on the towers of suspension bridges was investigated in (Casciati and Giuliano 2009).

Moving the attention to hangers, they are the critical components of suspension bridges, and short hangers are prone to damage under cyclic bending stresses. Cable clamps are key joints that connect adjacent structural components: they provide a suspension point for the series of vertical hanger cables, which carry the deck. Their vibration should be controlled, but the significant developments in the passive and active control of the obliquus cables of cable-stayed bridges that cannot be directly applied to the vertical hangers of suspension bridges.

Eddy current dampers (ECD) were recently developed for this purpose. In an ECD system, the circulating eddy currents are generated in a conductor when there is a relative motion between the conductor and magnetic field. A resistive force will cause energy dissipation due to the electrical resistance. The resistive force induced by the eddy currents is proportional to the relative velocity. Therefore, the damping system can be described as a form of viscous damping, as well (Niu *et al*. 2018).

7. Conclusions

In (Ge 2016), the author, who also served as co-author for several papers mentioned in the references list of this paper, goes further the actual realizations. He writes: "It seems that the intrinsic limit of span length due to aerodynamic stability is about 1500 m for a traditional suspension bridge, but slotted box deck could provide a 5000 m span length as the aerodynamic limit to a suspension bridge with high enough critical flutter and torsional speed". As a support the author disseminates details on ongoing feasibility studies starting from the Shuangyumen Bridge, with span of 1768 m. With the companion cable-stayed Qinglongmen Bridge, it will connect Liuheng, Fodu islands in Zhoushan (Zhejiang province) and Meishan Island in Ningbo. The construction will involve a total investment of 1.81 billion and take 57 months to be completed. The author also reports on the second Sunda Strait Bridge of span 2018 m. (the first bridge being similar to the Messina strati Bridge of span 3300 m), and the Taiwan Strait Bridge of span 5000 m. Along the way, the Gibraltar Strait Bridge, actually three spans of length 3500 m, is also mentioned.

The studies above reported are mainly based on aerodynamics studies of the wind effects on such long span bridges. Nevertheless, updated design rules should add resilience to the standard reliability-robustness-economy triplet and this concern is hard to be satisfied for very long span bridges: even a localized collapse would make the structural skeleton difficult to be engaged by the recovery vehicles and equipment. The access would be only possible from the surrounding sea/water level.

Speaking in general, the required huge height of the piers would also make more and more onerous the maintenance of the main cables, while some of the hangers become definitely quite long. Finally, a link conceived for high speed trains requires a runability that has still to be checked for bridges of main span longer than 1000 m.

The progresses in foundation technology would suggest investigating the possibility of several shorter spans according to De Miranda (2022). If this is not possible, geometry and control arrangements should be pursued already at the design stage. At this stage, also the monitoring should be accurately planned.

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Appendix A

For sake of completeness, two list of successfully Chinese infrastructures are given. The first list provides the infrastructures ranked in terms of length of the connections:

- the Hong Kong-Zhuhai-Macau Bridge, 55 km long, completed in October 2019 (currently the longest connection built worldwide),
- the Hangzhou Bay Bridge, 36 km long, inaugurated in 2007 and opened in May 2008,
- the Donghai Bridge, 20 miles long, which was the longest bridge across the sea when it was built in 2005,
- the Sutong Chinagjiang Highway Bridge, 19.9 miles long, main span cable stayed (2010),
- the two bridges arched Lupu Bridge Shanghai (3791 m, year 2003) and
- Chaotianmen Bridge (1741 m, year 2009).

In this list, all bridges are vehicular. The oldest (1968) bridge of this class is also allowing the railway crossing. It is the Nanjing Yangtze River Bridge, of length 6772 m, but with a maximum span of 160 m.

The second list provides the Chinese bridges ranked in terms of orographic height of the connections:

- the Jiaozhou Bay Bridge in Qingdao, in Shandong Province;
- the dizzying Duge Beipan River Bridge, in Guizhou Province;
- the Aizhai Bridge, in Hunan Province, located between two tunnels and
- the Beipan River bridge incorporated in the Shanghai-Kunming high-speed railway in Guanling Buyi and Miao Autonomous Prefecture in Anshun. The latter, built in an arch, runs 968 feet (about 300 m) above the Beipan River.

Further details on all these bridges are easily found in Wikipedia.