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BEARING SYSTEMS FOR HIGH SPEED RAILWAY BRIDGES

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ABSTRACT

High speed railways will be one of the most important challenges for the structural engineers of the third millennium and the aspect of the structural bearings has an important impact on the design of the structures.

The bridges for the high speed railways, even if their static scheme is often very simple, are peculiar structures where the interactions between ballast, rail and bearings play a fundamental role.

An important aspect of the bearings for high speed railways, frequently requiring special solutions, is also the high level of the horizontal loads that are due to braking and traction forces and in many cases to the earthquake. In some cases, for instance high level of earthquake, also uplift forces shall be considered.

The author, currently involved in the design and supply of the structural bearings for the largest high speed rail projects in the world (Italy, Taiwan and China), describes the different solutions of the bearing systems utilised in many projects around the world, putting in evidence their impact on the design of the structures.

The problems related to the installation of the bearings, considering that in many cases the over structure is prefabricated, are also analysed.

Moreover normative aspects, quality assurance and tests are treated.

The aim of the paper is the review of the possible bearings systems putting in evidence their performances and the problems related to their utilisation, providing also a guide to the designers for the selection of the bearings.

Keywords: Standard, structural bearings, pot bearing, spherical bearing, shear keys, railway, high speed railway

INTRODUCTION

Indeed the construction of railways will be one of the most important issue for the civil engineer in the next decades, world wide.

The European high speed rail system was proposed in 1985 by the EC and includes 23000 km of line, more of half of which to be newly built. According to the programs the European system shall be completed in 2010 (this date, foreseen in 1985, doesn’t seem to be realistic today). At present time the most important sections under construction are in Italy (Milan – Turin, Milan – Bologna, Bologna Florence for a total length of 350 km) but very soon will be started other sections again in Italy but also in Portugal and other European countries.

Outside Europe there are also many thousand km under construction or planned in the near future, specially in Japan, China and other nations under development.

The design speed of the trains, normally 350 km/h, imposes severe geometrical limitation to the track layout in terms of minimum radii of curvature (R > 7000 m), maximum camber under load (1/3000 of the span) and maximum gradient (< 1,8%), so that, when the line crosses highly urbanised areas the ratio of bridges to track length is very high. For instance from Milano to Bologna, a relatively flat area, there are 50 km of bridges on 180 km of track, and from Taipei to Kaoshung in Taiwan there are 250 km of bridges (approximately 8000 spans) on 350 km of tracks.

Bridges are therefore quite often a very relevant part of high speed railways.

Bridges for high speed railways however shall first of all respond to the requirements of the line and not vice versa. As many responsible of the Railways organisation claim: the structure is a service for the rail. In addition to the above mentioned geometrical and stiffness requirements the most stringent one is given from the fact that the rail shall be continuous, avoiding as far as possible the joints on it. This fact is surely due to the comfort (joints of the rail cause noise to the passengers and to the environment) but also to maintenance problems that would be increased by the presence of joints in the rails.

Structures like bridges are subjected to length variations that are normally restrained in one point (the fixed bearings) and causes a concentrated movement, proportional to the distance from the fixed point, at the ends of the structure.

The simply supported beam is the preferred static scheme for the railway bridges because, thanks to the presence of the ballast allowing small movements between the rail and the bridge deck, it makes possible the adoption of continuous rails, with great advantage for the maintenance of rails and rolling stock and for the comfort of the passengers. Continuous bridges, requiring expansion joints in the rails, are normally limited to important river crossings or in proximity of the stations.

Therefore the simply supported beams has been adopted in many nations as the main rule, for instance in Italy, Germany, Taiwan, Japan, China, although with some important exceptions like Spain and France.

Even if the static scheme of the bridges is normally very simple, high speed railway bridges are peculiar systems where the superstructure interacts with ballast, tracks and vehicles from one side and with the structural bearings from the other side in a complicated manner, involving strongly non linear effects.

In the paper are described the different static schemes frequently adopted for the railway bridges, the possible bearing systems and their impact on the design and the behaviour of the structures

FREQUENT STATIC SCHEMES ADOPTED FOR THE HIGH SPEED RAILWAY BRIDGES

The adopted static scheme varies in function of the ground morphology but may be easily classified in three categories:

a) When the line passes through a flat country crossing roads and small rivers the preferred scheme is the simply supported beams with spans ranging between 25 and 35 meter (see Fig 1). The length of the spans rarely exceeds these values because the structure shall provide a sufficient stiffness in order to limit the flexural deflection due to live load to 1/3000 of the span or less. Normally the bridge structure consist of single or twin box girders of prestressed concrete. When the roads or small rivers to be crossed are frequent, as normally happens in highly urbanised areas, the bridges may become very long as a result of the gradient limitations. A typical example in this sense is the viaduct Modena with a length of 18 km (see Fig 2).

   Within the Italian territory the above described static scheme represents nearly the 90% of the entire bridge length of the line.

b) When the line crosses deep valleys a very frequent solution consist of reinforced concrete arches supporting concrete beams with span ranging between 15 to 25 meter.

c) In case of important river crossings, requiring large spans, the preferred solutions are always those minimising the distance between the rail level and the structure intrados, in order to reduce as much as possible the necessary gradient, hence reducing the need of approach bridges or embankments. The structures normally adopted in these cases are:

- Steel or concrete arches with lower railway and hangers for spans up to 100 meter. However this type of structure has been adopted for the 180 meter span Yi-Chang bridge in China (see Fig 3 and 4)
- Steel trusses with lower railway for spans up to 150 meter
- Steel or concrete cable stayed bridges for spans over 150 meter
- Suspension bridges for bigger spans. The bridge over the Messina strait, recently awarded, will represent the world record with its 3300 meter span, although the speed will be limited

BEARING SYSTEMS FOR THE .HIGH SPEED RAILWAY BRIDGES

The bearing system for a structure, as defined by EN 1337-1, is the combination of bearings and structural devices which together provide for the necessary movement capability and for transmission of forces.

The selection of the suitable bearing system for a railway bridge shall always be made taking into consideration the following peculiar requirements:

- Horizontal loads due to braking and traction are very high in comparison with the vertical reactions. This require a special consideration on the way this forces are transferred to the substructures. The problem is amplified if also earthquake forces have to be considered.
- The continuous rails are interacting with the structure, specially for the transmission of the longitudinal load. The bearings shall be able to transfer the longitudinal loads with the minimum possible deformation in order to avoid as much as possible an axial reaction from the rail that may cause buckling and misalignment. Elastomeric bearings shall therefore be excluded, unless combined with rigid restrains.

- In case of earthquake the lateral deflection of the piers may be out of phase, so that the spans may rotate around the vertical axis, requiring the same capability to the bearing system.
- In case of very strong earthquake the bearings may be subjected to uplift forces as a result of two possible situations: lateral earthquake with one train on the track and out of phase lateral deflection of the piers when the bridge deck has a very high torsional stiffness.

The possible bearing systems for simply supported spans railway bridges are summarised in the figure 5.

Scheme N. 1, although fulfils all the above mentioned requirements, is not very often adopted having a great disadvantage: the horizontal longitudinal force is transferred to the pier out of centre, this means that, in presence of high forces the pier is subjected to torsion.

Scheme 2 has been adopted in some cases because apparently is the cheapest solution but also presents a very negative aspect, due to the fact that different bearings don't react in the same way to horizontal loads.

In a fixed pot bearing for instance the horizontal load will be transferred only after the following mechanical gaps between bearings components have been compensated:

- Gap between lower anchor bolts and bearing plate: normally 0,3 mm
- Gap between pot and piston: normally, in accordance with EN 1337-5, a maximum gap of 0,5 mm is allowed with non metallic seals as required for railway bridges
- Gap between upper anchor bolts and bearing plate: normally 0,3 mm

In a transversally guided sliding bearing, to the above gaps the following one shall be added:

- Gap between guide bar and sliding plate: normally, in accordance with EN 1337-2, a gap of 1 + L/1000 mm, where L is the length of the guide is accepted. For the frequent case of bearings with a length of the guide of 1 meter the gap becomes 2 mm (see Fig. 6).

In conclusion for fixed bearings the total sum of the gaps is 1,1 mm and for the sliding guided is 3,1 mm. Even if this values can be reduced with a very accurate machining (but with a higher cost !), it is clear that the gaps cannot be made equal to zero. Furthermore it cannot be predicted in which direction the gaps will provide a clearance (unless adopting special equalising devices that will be described for scheme 5) and therefore they shall be considered in such a way to give the worst conditions. The result is that one of the two bearings foreseen in the fixed axis of scheme 2 will react first, giving to the pier an eccentric load that will cause a torsion and a bending.

Only when the displacement of the pier in correspondence of the second bearing will fill the existing clearance the second bearing will begin to react to the horizontal loads. The required displacement may be as big as 4,2 mm, that renders this solution applicable only if the piers or the bridge deck are very flexible. It shall be considered that, as a consequence of the non simultaneous reaction, each of the two bearings shall be designed for a horizontal force that is higher than 50% of the total and in some cases, when the piers are very rigid, can be near to 100%. In other words the two bearings shall be designed for a horizontal force up to 200% of the actual one with negative impact on the total cost of the bearing system.

In addition this solution don't allow the rotation around the vertical axis and therefore presents a further negative aspect in presence of earthquake.

In conclusion Scheme 2 cannot be recommended, even if it has been adopted in important jobs.

Schemes 3 and 4 are indeed the preferable ones because they transfer the loads to the substructures in a clear and statically determined way, allowing the free movements as required in earthquake conditions. In particular Scheme 3 normally represents the best ratio performance/cost. Scheme 4 is some times required if the bearings cannot resist any horizontal load, like for instance antivibrating elastomeric bearings.

Scheme 5 represents the Italian approach to the problem and consists in the adoption of fixed bearings equipped with an elastic restraint providing a horizontal load reaction increasing with the horizontal deflection. Horizontal load and deflection shall fit a very narrow domain as required by the Italian Railway Authorities and shown in the attached scheme (See Fig. 7). The total deflection is very limited and cannot exceed 1,25 mm. In this way the reactions of two fixed bearings placed on the same fixed axis can be equalised.

For the continuous bridges there will be one fixed axis and several movable axis adopting the same solutions of the above described Schemes, with preference for the schemes 3, 4 and 5.

Quite often the horizontal load to be transferred to the fixed axis is very high and would require excessively resistant piers, specially in presence of earthquake.

A frequent solution in this case is to place on the movable axes Lock-up Devices that allow slow movements due to thermal creep and shrinkage effects with negligible reaction whereas resist rigidly to dynamic forces like braking and earthquake. The use of Lock-up devices however must be carefully evaluated bearing in mind their actual performances. First of all it shall be considered that Lock-up devices require a small movement, of the order of 3 mm, to reach the design load. Therefore it is required that the fixed axis is not perfectly rigid but allows a small deflection under horizontal load to allow Lock-up devices to be activated. In addition it shall be noted that the braking forces generated by trains, differently from the forces generated by earthquakes, may remain nearly constant for a period of 30 seconds or more. Therefore it is required that the Lock-up Devices are designed to resist the required force for such a period with negligible or acceptable displacement (See Fig. 8).

TYPES OF BEARINGS ADOPTED FOR THE HIGH SPEED RAILWAY BRIDGES

The pot bearing is for sure the most frequently utilised one for high speed railway bridges, with one important exception that is Italy. The reasons for this exception will be explained later.

Pot bearings mainly consist in a rubber disc encased in a steel pot closed by a steel piston. The rubber is subjected to a very high pressure, of the order of 30 Mpa and is prevented to be extruded through the gap between pot and piston by a seal that is frequently made of synthetic materials, specially for railway bridges applications. Pot bearings in fact realise the spherical hinge with the minimum possible restoring moment, therefore providing the best conditions for a long service life of the PTFE sliding surfaces. Besides, fixed and sliding guided pot bearings are suitable to transfer high horizontal loads in a reliable way, also in absence of vertical load. The most frequent feature of a sliding guided bearing is shown in fig. 9. If the horizontal load shall be transferred also in absence of vertical load the feature is different and becomes very similar to that of the movable shear keys that will be described later. In this case the sliding guided pot bearings shall be specially conformed with the guides at the same level of the contact pot-piston in order to avoid undesirable moments. Fig. 10 shows this arrangement applied to a movable shear key.

In areas subjected to strong earthquakes, like Taiwan, the bearings may be required to resist uplift, resulting from the combination of a transversal earthquake with the eccentric load of one train or from out of phase displacements of the piers in presence of a bridge deck very rigid to torsion, like for instance prestressed concrete box girders. In that case the bearings shall be provided with an anti-lifting device. Since the uplift force may be considered as a result of a very rare loading combination in ULS conditions, normally it is not required to the anti-lifting device to provide rotation capability. For the Taiwan high speed railway antilifting devices have been realised as shown in fig. 11 by two lateral clamps. Their plastic deformation up to a strain of 0,01 is taken into account in order to accommodate the rotation at ULS.

The most common bearing for the Italian high speed railway however is not the pot bearing but the spherical one. Spherical bearings have the advantage in comparison with pot bearings to allow a much greater rotation. Normally the rotations in railway bridges are very small due to the deflection limitations: a defection of 1/3000 of the span corresponds to a rotation on the bearings axes of 1,3 milliradians where the allowable rotation of pot bearings is normally much greater, of the order of 10 milliradians. In Italy a very large part of the railway bridges are made of prefabricated beams and it is very convenient to accommodate the prefabrication tolerances, normally of the order of 5 to 10 milliradians, utilising part of the rotation capacity of the bearings. In this way it is possible to place the prefabricated beam directly on the bearings avoiding the use of temporary supports. For this reason the Italian Railway authorities selected the use of bearings with rotation capacity of ± 3° corresponding to ± 52 milliradians, largely sufficient to absorb both flexural rotations and prefabrication tolerances. In this case however it is essential to install the bearings with the sliding surface on the bottom. The sliding surfaces are installed perfectly horizontal and are not affected by the rotation of the bearing due to the prefabrication tolerances. In this way one can be sure that all the sliding surfaces are parallel. The stainless steel of the sliding surfaces must be protected by a suitable dust cover in order to avoid accumulation of dust or debris on it.

The bearing layout normally adopted in the Italian high speed railways is the scheme 5 as described in the previous paragraph. Two fixed bearings are placed on the fixed axis. They are equipped with an elastic restraint that is able to equalise the horizontal loads in the two fixed bearings. In the example of fixed bearing shown in Fig. 12 the elastic restraint consists in a steel ring acting between the upper steel plate with concave sliding surface and the lower one with flat sliding surface. The steel ring is stressed by bending and torsion by the horizontal load. The horizontal load deflection plot of the fixed bearing shall be included in the domain defined by the Italian railway authorities shown in Fig. 7 and one prototype bearing selected at random shall be tested for every delivery lot. As it may be seen from the diagram the horizontal deflection under load is very small and requires a very accurate machining.

A few percent of the bearings installed in the Italian high speed railway is required to be equipped with a load cell as in the example shown in Fig. 13.

Shear keys are utilised with schemes 3 and 4. They are very similar to pot bearings with the important difference that they don’t have a rubber disc since they are not asked to bear a vertical load. The absence of vertical load requires the movable shear key to be conformed as shown in fig. 10, with the contact line between the pot and the piston aligned with the centre of the sliding surface. Both fixed and movable shear keys are free to rotate around the vertical axis thanks to the circular contact between the pot and the piston. The rotation around the vertical axis is specially required in seismic areas to compensate the out of phase movement between the piers.

Shear keys shall be designed to allow small vertical movements to compensate the deflection of the bearings under load without reaction.

NORMATIVE ASPECTS

The European Standard on Structural Bearings is now a reality and all partners involved in the construction of a High Speed railway –owners, designers, supervisors, contractors and specialist suppliers- shall be aware of that.

It may be seen that for the spherical bearings the application of the European Standard is already compulsory, whilst for all the other types of bearings this will happen in less than one year. It is clear that the use of the old Standards (for instance DIN, BS or UNI) could only be admitted for projects that are now under construction. All new projects shall be exclusively based on the relevant parts of EN 1337.

It shall be emphasized that the European Standard EN 1337 has been already adopted also outside Europe for 2 very important projects:

- The Taiwan High Speed Rail
- The China High Speed Rail

CE mark represents a certification that the products have been manufactured and tested in accordance with the relevant parts of EN 1337. According to the CEN rules the final user of the bearings cannot require supplementary tests or controls to verify the conformity to the standards.

However the final user may require to the bearings supplementary requirements that may be subjected to further tests or verifications.

The following are two important supplementary requirements that are requested by the Italian High Speed Railways Authorities:

- Bearings shall be dielectric. This requirement aims to avoid the propagation in the structures of the so called stray current, connected with the power supply of the train which may cause corrosion effects on the steel reinforcement. Bearings in Italy are required to be intrinsically dielectric (it means without the application of external paintings or insulating materials) with a minimum resistance of 10^6 Ohm at 100 V.

- The fixed bearings shall be equipped by an horizontal load equalization system as described at paragraph 4.

A FEW OUTSTANDING CASES

Taiwan High Speed Rail with its 8000 spans over a length of 350 km, completely built in 30 months, for sure represents by itself an outstanding case, but is also remarkable for the following aspects:

- Has been the first application, world wide, of the European Standard EN 1337. Although not yet completely approved at the time of tender, the standard in it's 1996 draft has been included in the tender documents end therefore became compulsory for the job. It has been applied to the design, manufacture, quality control and testing of around 32000 pot bearings in accordance with EN 1337-5 and 2000 shear keys in accordance with EN 1337-8
- Include some exceptional structures that are described here below

There are three steel bridges crossing the river, near the Taichung station. The most outstanding is that shown in Fig. 13. It consists of a continuous steel truss with maximum span of 150 meter and a beam height of 18 meter.

The bearing layout is shown in Fig. 14 and slightly differs from the schemes described at paragraph 3. The fixed axis (axis N. 2) is provided with 2 transversally guided bearings resisting the longitudinal horizontal loads and a movable shear key resisting to the transversal horizontal loads.

Since the steel superstructure is relatively flexible the longitudinal horizontal load can be shared in approximately equal parts among the two guided bearings that can also provide sufficient transversal movement capacity to absorb the thermal effects.

For all the other axes of the bridge are foreseen a longitudinally movable shear key and two free sliding bearings allowing longitudinal and transversal movement.

The bearings adopted for this bridge are also absolutely outstanding for what concerns their bearing capacity.

Bearings on axis N. 2 are designed for a vertical load of 82200 kN and a longitudinal horizontal load of 21000 kN. The shear key on the same axis is designed for a transversal horizontal load of 31000 kN. It is shown in Fig. 15 and its own weight is of 32 ton

An other exceptional application of special bearings has been adopted in the Taiwan High Speed Railway.

Part of the railway, for a length of 5 km approximately, crosses an important Hi-tech industrial park in which many industries very sensible to vibrations will be located. To reduce the vibrations in the surrounding environment flexible structural bearing has been adopted, realising the so called mass-spring-system. The mass-spring-system is well known to be the most efficient solution to reduce vibrations and in this case it is particularly performing due to the fact that the mass supported by the flexible bearings consists of the entire bridge superstructure and superimposed dead loads. The vertical stiffness of the bearings has been selected in order to obtain a natural frequency of the superstructure for vertical vibrations of the order of 10 Hz, providing a sufficient gap with the natural frequency of the vehicles from one hand and the frequencies of structure-borne sound on the other hand. The bearings with the required vertical stiffness has been developed utilising a very low damping natural rubber compound suitable to minimise the dynamic stiffening effect. They have been designed for the service conditions -vertical loads and flexural rotations - in accordance with the European Standard EN 1337-3. The horizontal movements due to creep, shrinkage and thermal effects are allowed, at the movable end of each span, by PTFE and stainless steel sliding surfaces in order to minimise the shear deformation of the rubber. All horizontal loads due to service and earthquake loads are supported by mechanical shear keys totally independent from the rubber bearings. The bearing system reflects scheme 4 as described at paragraph 3, with elastomeric bearings acting as free sliding ones.

An antivibrating bearing installed under the bridge is shown in fig. 16 and 17. The same kind of bearings have been utilized also in the Yi-Chang bridge in China to protect the environment from the vibrations.

Fig. 18 shows a section of the Taiwan High Speed Railway under construction.

CONCLUSION

High Speed Railway bridges, even if their static scheme may appear very simple, are peculiar structures where the interaction with the ballast and the rail from one side and the bearings from the other side, shall be evaluated carefully. There are several bearing systems that is possible to apply and the designer shall select the right one in function of the performance required. The aim of the paper has been the review of the possible bearings system putting in evidence their performances and the problems related to their utilisation.

The European Standard EN 1337 is the most complete and updated document on structural bearings and for sure will be able to provide the necessary warranty of good performance and quality of these important structural devices

Fig. 1 Simply supported spans of 25 to 35 meter represent the most frequent structural scheme for most of the High Speed Rail bridges like Taiwan as shown in the picture

Fig. 2 The Modena viaduct of the Italian High Speed Rail. Simply supported spans of 35 meter for a total length of 18 km

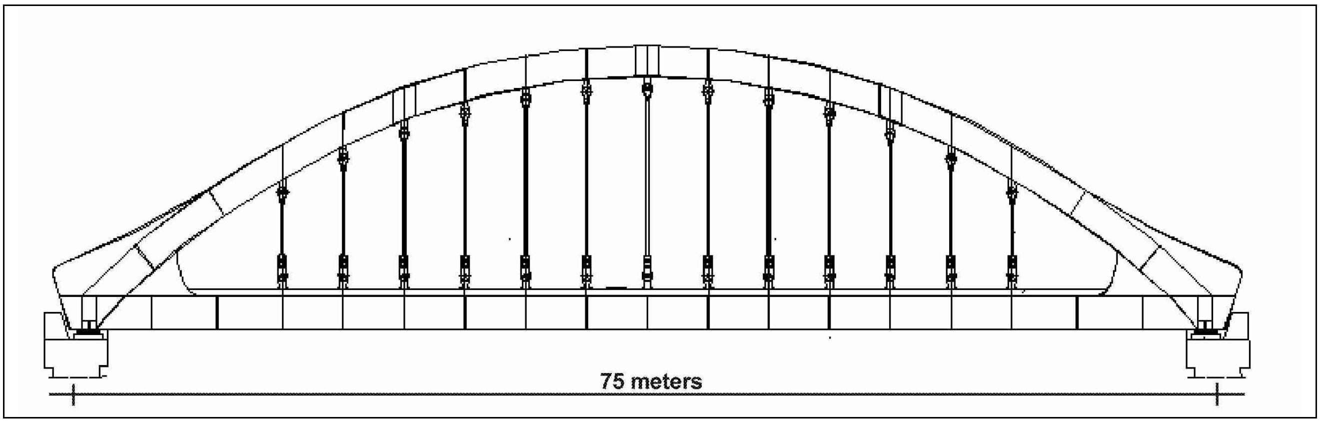

Fig. 3 A typical example of bow-string structure: the Savena viaduct on the Italian High Speed Railway

Fig. 4 An outstanding example of bow-string structure: the Yi-Chang bridge for the Chinese Rail System

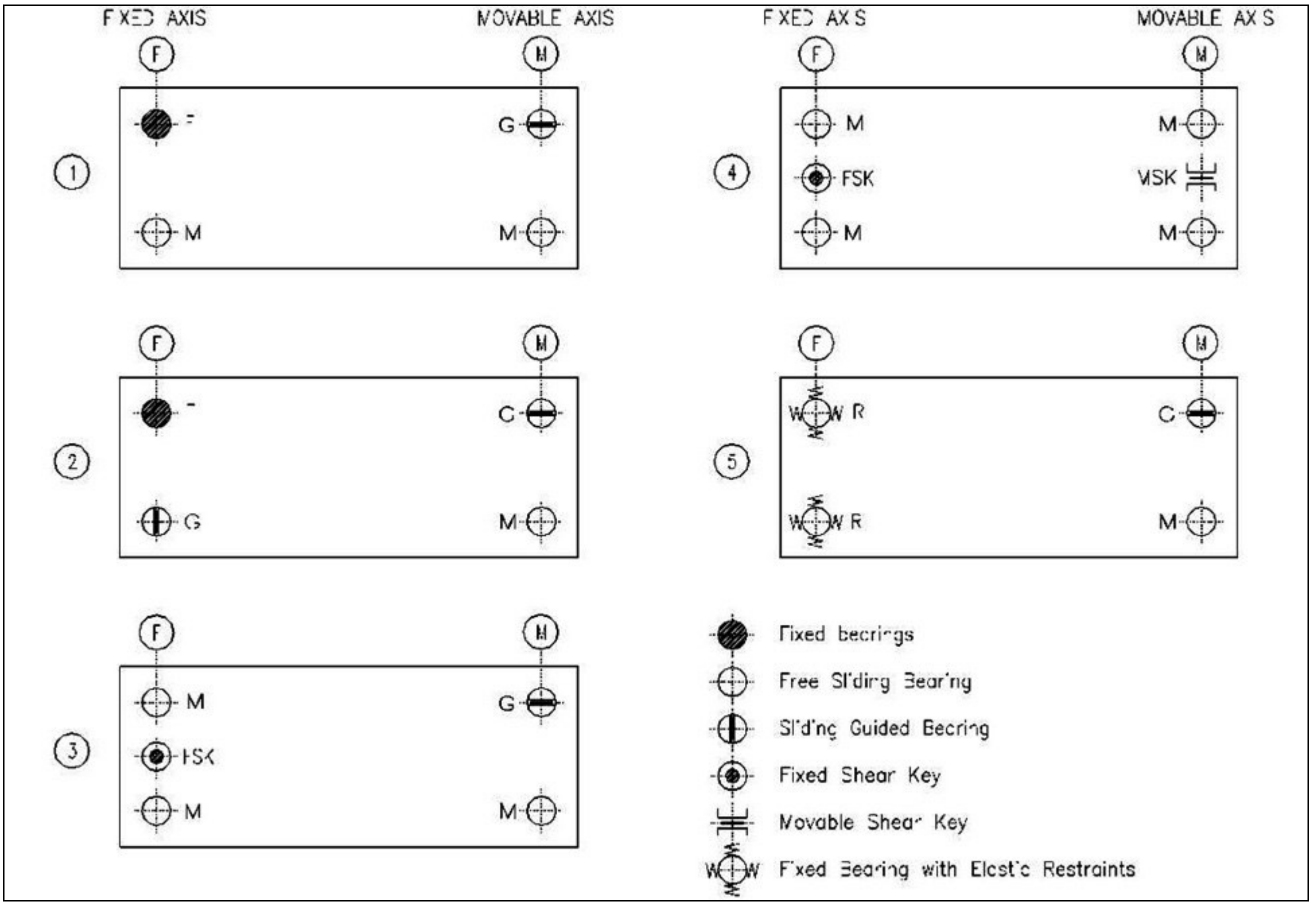

Fig. 5 - The possible bearing systems for simply supported spans railway bridges

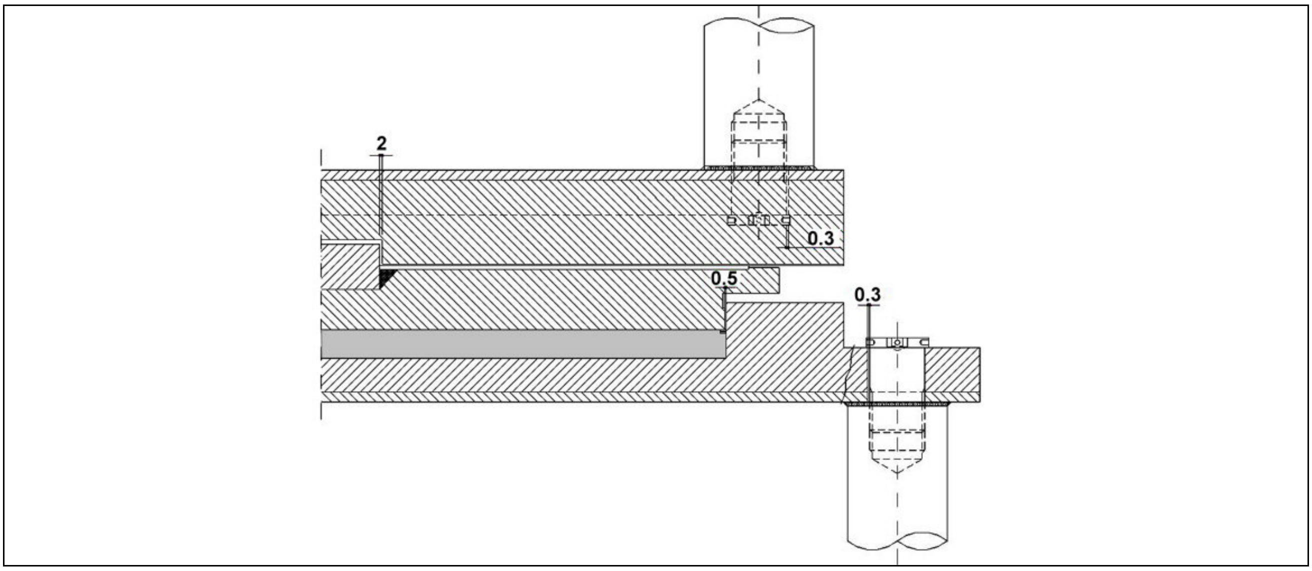

Fig. 6–Mechanical plays in a sliding guided bearing

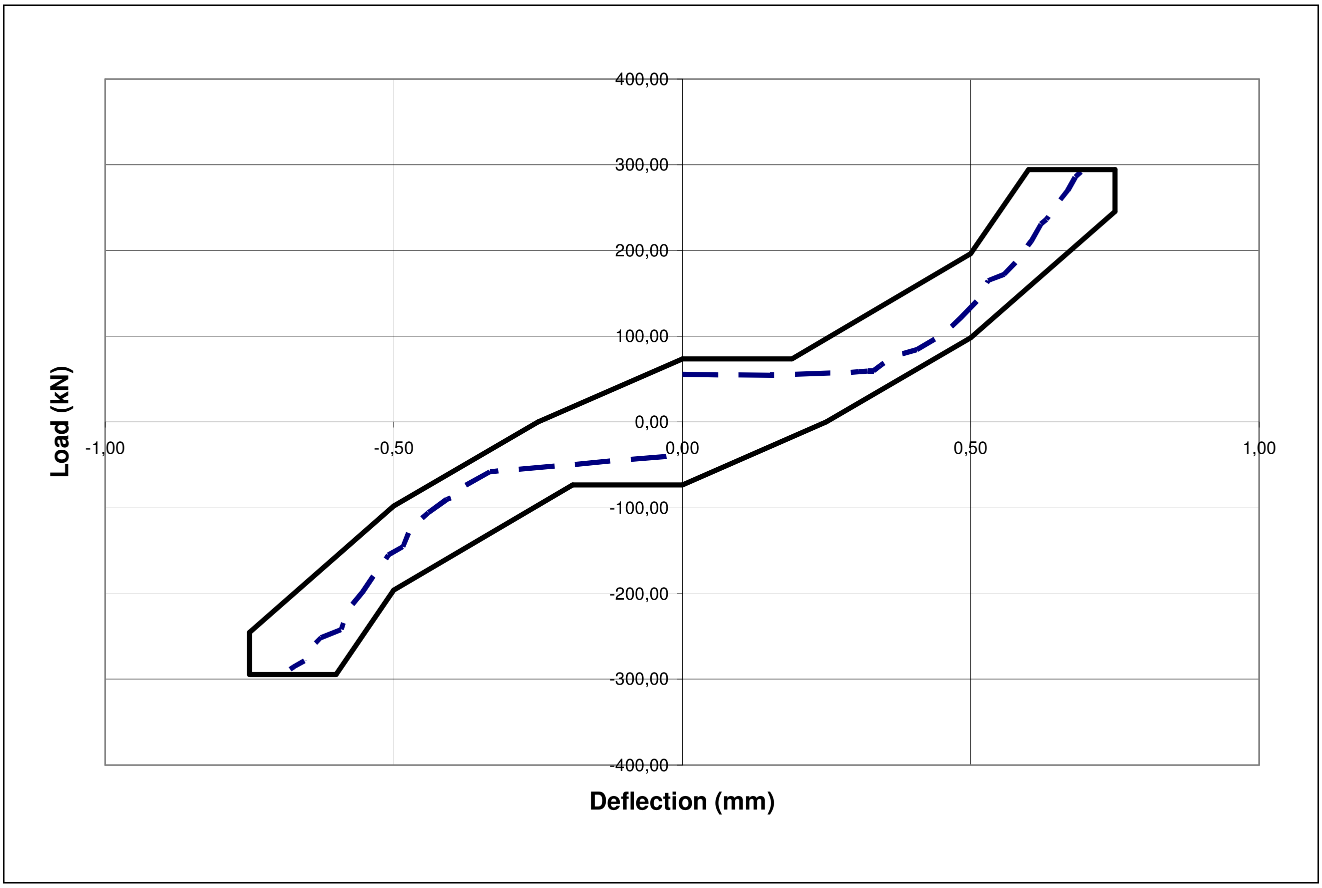

Fig. 7 – The domain horizontal load – horizontal deflection required for the fixed bearings with elastic restraint utilized by the Italian Railways compared with an experimental result.

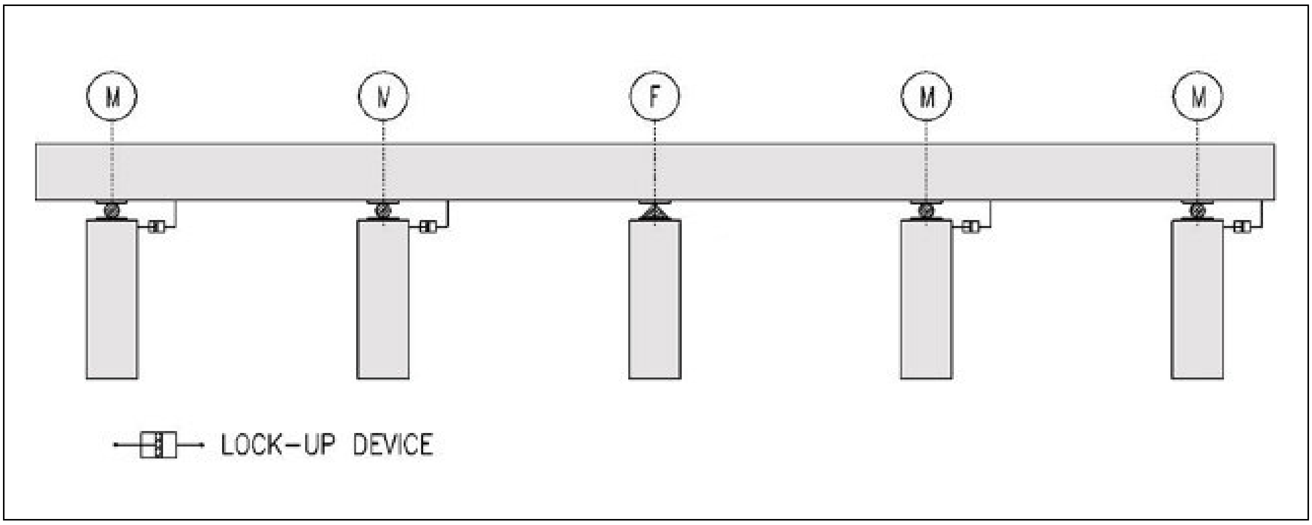

Fig. 8 – Continuous bridge with lock-up devices

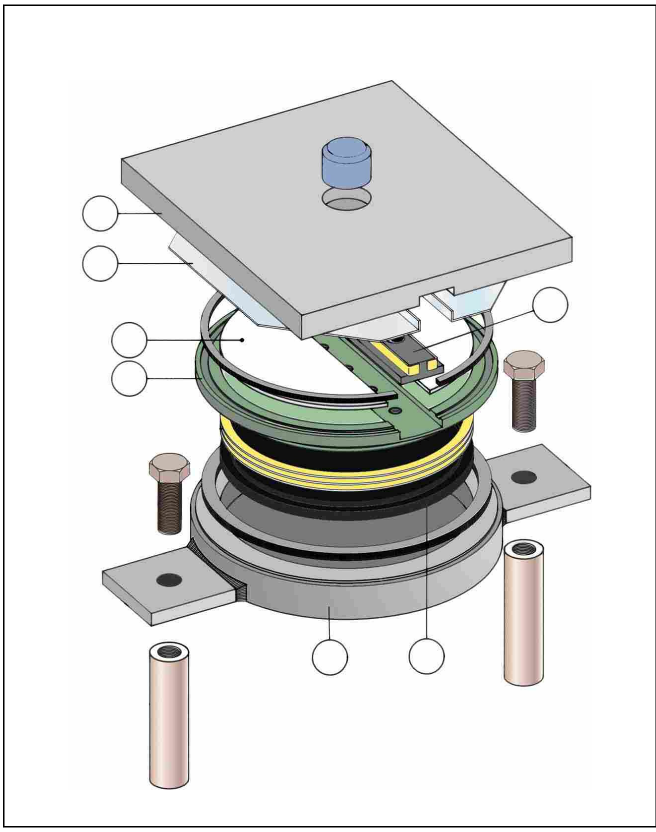

Fig. 9 The typical feature of a sliding guided pot bearing is not suitable if the horizontal load may be applied with a small vertical load

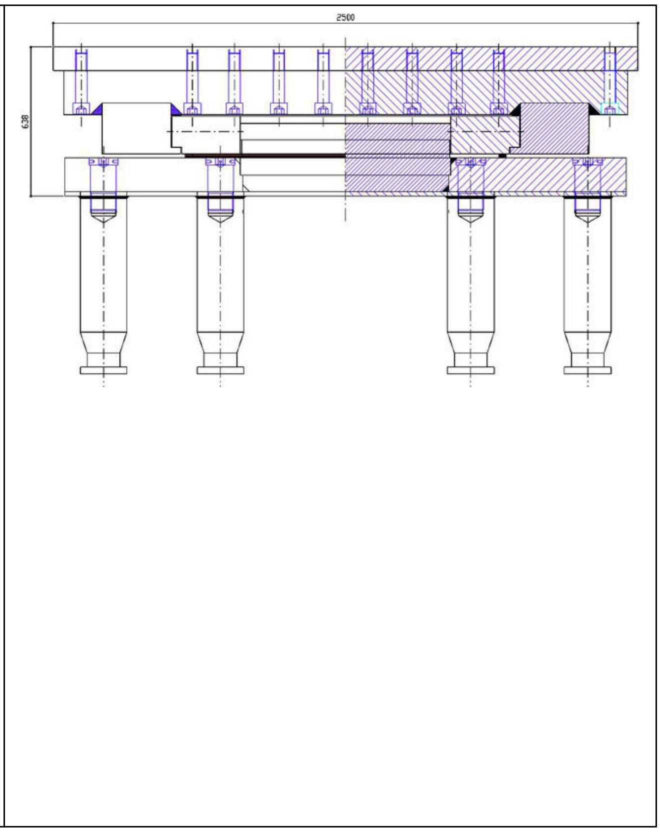

Fig. 10 Special feature of a sliding guided pot bearing with the guides aligned with the pot-piston contact level to withstand large horizontal loads in absence of vertical load

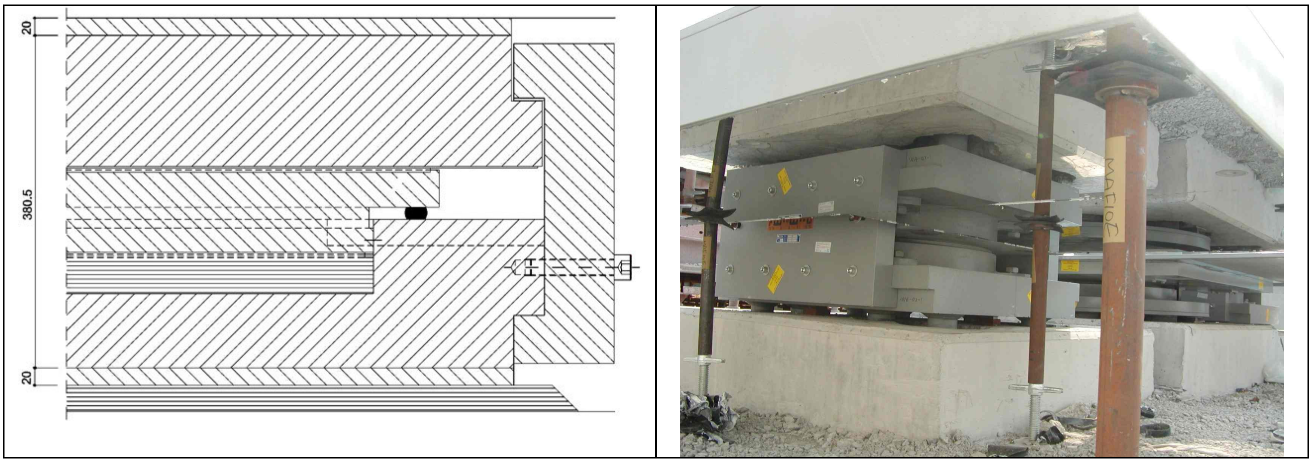

Fig. 11 Detail of the antilifting clamps utilized for the Taiwan High Speed Rail

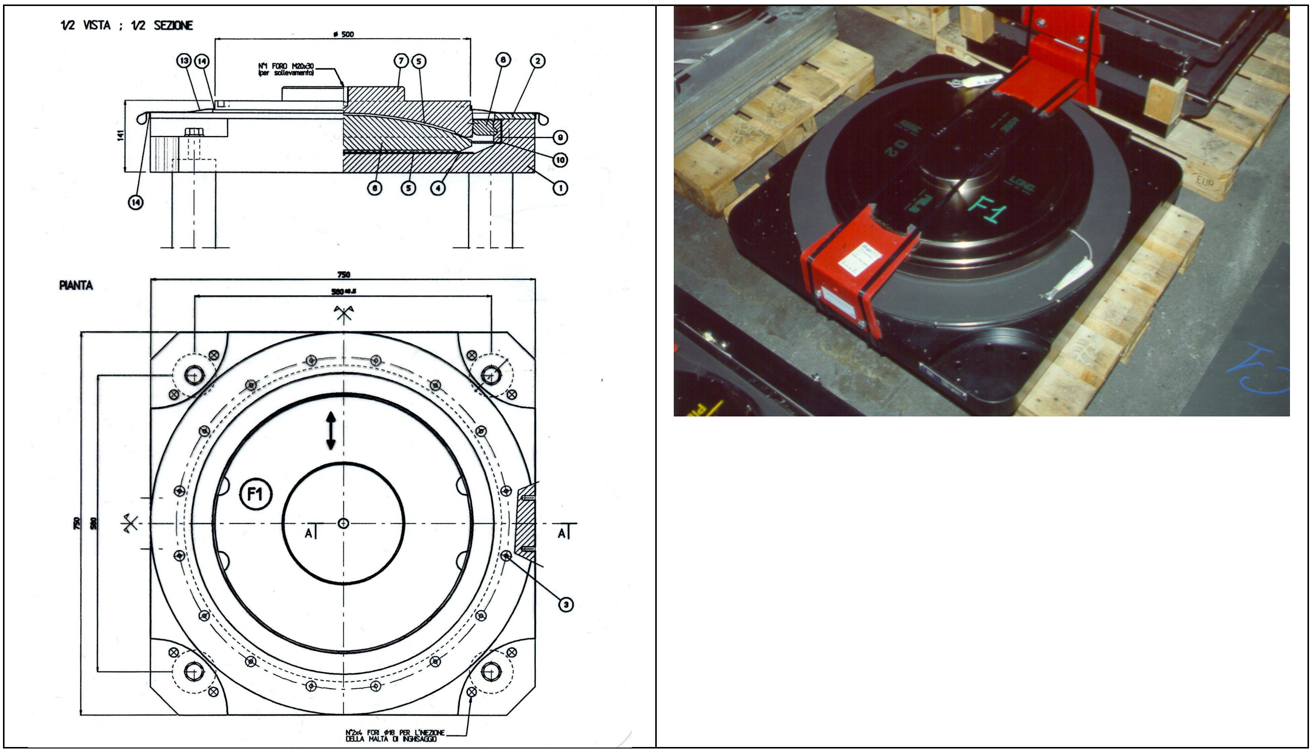

Fig. 12 – A fixed spherical bearing utilised for the Italian high speed railway.

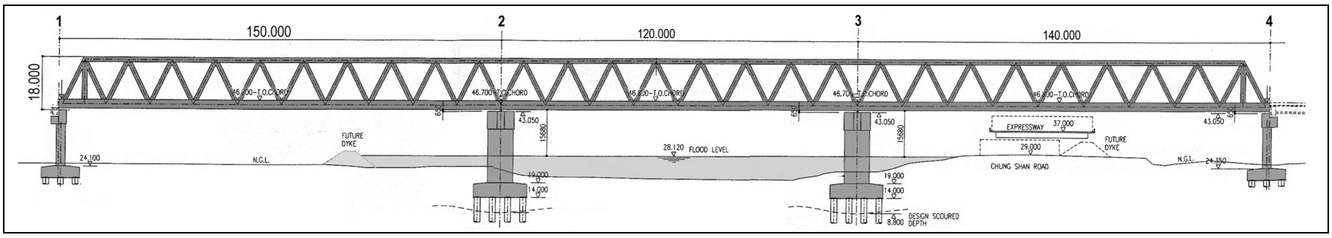

Fig. 13 The steel bridge near Taichung station of the Taiwan High Speed Railway. Piers 2 and 3, even if subjected to very different horizontal loads have the same geometry for aesthetic puprposes

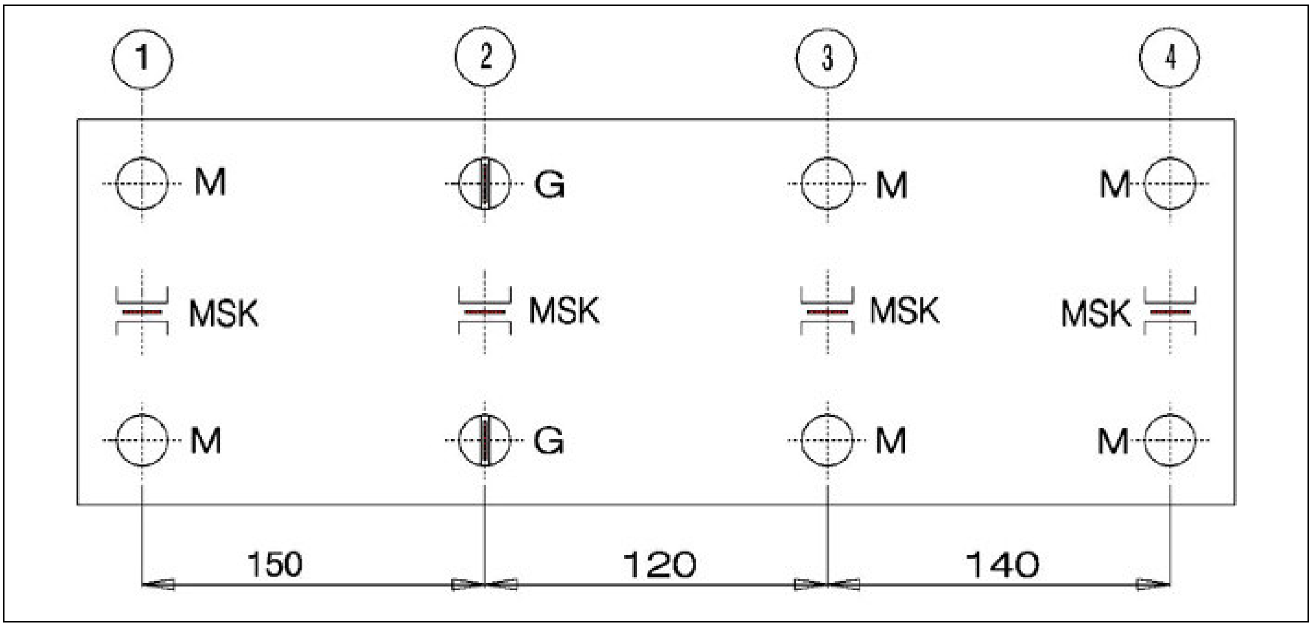

Fig. 14 Bearing system of the bridge over the river in Taichung

Fig. 15 – Giant shear key for the Taiwan High Speed railway. The red steel plates are intended for installation purpose only

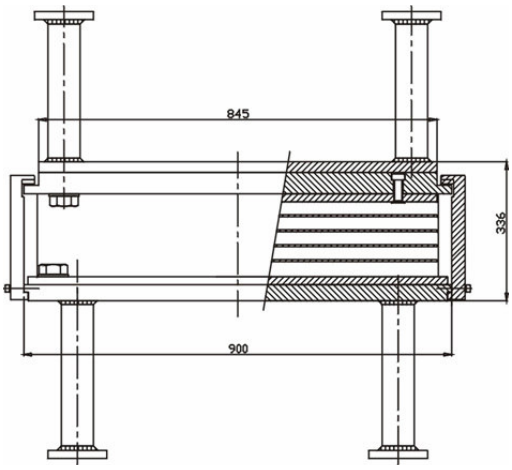

Fig. 16 – 17 Antivibrating bearings for the Taiwan High Speed Railway. Picture 16 shows the assembling phase in the factory; Fig. 17 the scheme. The lateral vertical steel plates shown in the scheme (not yet applied in Fig. 16) are anti-lifting devices

Fig. 18 The Taiwan High Speed Railway under construction