Examples for seismic isolation system fulfilling no damage criteria and with continued functionality

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ABSTRACT

Seismic isolation is meanwhile a well established approach to reduce forces and accelerations within structure in earthquake prone regions. However to satisfy even no damage criteria and absolute structural and content functionality after the earthquake, isolation systems need to consist of reliable, durable and effective hardware devices. This paper shows at the example of a railway bridge in Mexico and a hospital in turkey how such isolations systems were realized considering severe demands regarding damages and functionality after the earthquake.

The first example is Toluca–Mexico City Intercity Train, which will connect the metropolitan areas of Toluca with Mexico City. The seismic acceleration of max. 0,77 g for 1 s structural period represents a major challenge for the long Viaduct 2 - with a total length of 3,8 km. Strengthening design of the structural members was technically not possible anymore even knowing that it also would not be economical. The applied longitudinal seismic isolation, lateral guiding and hydraulic damping system according to EN1998 and EN15129 will significantly reduce the longitudinal forces by approx. factor three to five in combination with reasonable displacements of the decks. The final goal of lesser total structural cost as well as ensuring the safety of the structures and its functionality after seismic events was achieved with special high stress resistant and low friction bearings in combination with newly developed seismic railway joints.

The base isolation of the Eskişehir City Hospital will be explained as second case study, which is located 250 km south east of Istanbul in a rather highly seismic zone of Turkey with up to 0,6 g PGA. To avoid any fatalities or damages to the structure and enable absolute continued functionality even after the MCE event, it was decided to apply seismic isolation with highly durable curved surface sliders. This paper will show the design considerations to limit the base shear within the isolated building blocks for the MCE event down to less than 0.13 W (W = seismic weight = Dead Load + 0.3 Live Load) on isolator top level and max. 0.2 W on the upper floor building levels of the structure. For these low shear level requirements the isolator performance was adjusted to 3.5 s effective period and 26 % damping. Within severe third party testing campaigns in third party testing institutes the suitability and durability of the applied devices were chosen.

Keywords: Seismic protection system, isolator, viscous damper, isolation, no damages

CASE 1: TOLUCA- MEXICO INTERCITY TRAIN PROJECT

INTRODUCTION

Mexico City has the urgent need to improve public transportation towards the west where the town Toluca is located in a distance of 70 km. Therefore it was decided to establish this intercity train connection within which two rather long viaducts are located.

The Viaduct 2 is a structure of 3865 meters length, which is divided in five continuous sections whose respective lengths are between 690 metres and 850 meters. The Viaduct 4 is 1448 metres long.

Viaduct 4 is similar in design and construction however shorter. Therefore mainly Viaduct 2 due to its greater complexity will be described further on in this paper.

The decks of the viaducts will be built as a pre-stressed concrete box girder with a typical span of 52-64 m and it will be cast with a mobile scaffolding system. The most remarkable aspects of the design of the viaduct is its anti-seismic conception, due to the high seismic risk of the region.

On the final structural seismic design the applied bridge bearings, hydraulic dampers and railway expansion joints have special influence, i.e. effectively reduce the longitudinally acting forces while still controlling the displacements.

SEISMIC SPECTRUM

The seismic design spectrum was determined from a series of studies conducted by the National Autonomous University of Mexico (UNAM) in collaboration with IDEAM [1].

A return period for the determination of the design spectrum of 1475 years – also declared to be the MCE event - has been considered (Figure 1). The design spectrum has a maximum acceleration of 0.77g. A seismic spectrum for the construction phase with return periods of 9 years has also been defined

For seismic structural calculation the European Standard EN1998-2:2005 was applied.

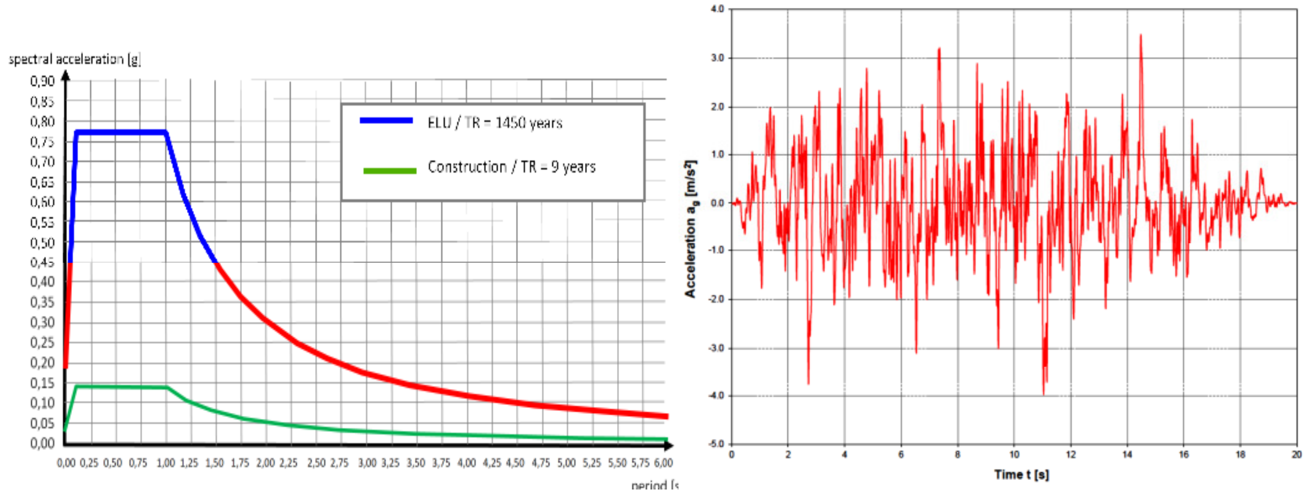

Figure 1 Response spectrum for 1475 years return period; on the right artificial accelerogram [2]

BEARING, DAMPER and EXPANSION JOINT SYSTEM

The bearing, damper and expansion joint system is able to provide thermal flexibility, longitudinal guiding, lock-up for service impacts and movement combined with energy dissipation. Therefore continued functionality will be ensured even after the maximum seismic events. EN15129 for anti-seismic devices was considered.

To achieve a significant reduction of forces acting due to seismic impacts on the deck, piers and foundations, the deck was decided to be longitudinally isolated allowing up to +/-300 mm displacements between deck and pier or deck and abutment.

The displacement control will be provided by viscous dampers and the system re-centering by elastic rubber springs. The re-centering forces and the damping forces were desired to be concentrated at certain locations and not shared to each single pier. The damper and re-centering forces had to be concentrated at abutments and delta piers, able to transmit longitudinal forces. The regular piers are only able to transmit 1-2% sliding friction forces of the foreseen spherical sliding bearings.

The deck is longitudinally guided and more or less rigid in lateral direction. This was achieved by guided spherical bearings, which in addition provide the required vertical load capacity for service and maximum vertical seismic effects.

Longitudinal system function

For the purposes of the longitudinal earthquake, each of the five continuous sections of Viaduct 2 behaves independently and for each section a fixed axis was selected to transmit braking, rheological and seismic forces. The other axes and piers are not transmitting these forces anymore. For the first and last section of the viaduct the fixed axes have been placed in the abutments while in the intermediate sections fixed axes have been placed on delta-shaped piers.

The longitudinal deck fixation for service braking and acceleration forces from the trains is provided by special viscous dampers on these relevant fixed axes (Figure 2). These dampers lock-up immediately for deck velocities of 1-2 mm/s and limit maximum deck displacements to typically 5-10 mm, required for service movements within railway bridges.

This specific lock-up behavior will retain the deck strictly in position for service braking or train acceleration due to the small damping exponent alpha of 0.04, as already 80% of nominal damper force (F_{AMORT}) level is achieved for 2 mm/s velocity:

$F_{AMORT} = C\, v^{\alpha}$ with F_{AMORT} = damper force, C = damping constant, v = velocity, α = damping exponent = 0.04

The maximum seismic longitudinal displacements will be effectively limited by energy dissipation with the same viscous dampers to approximately maximum ±294 mm and related velocities of 610 mm/s.

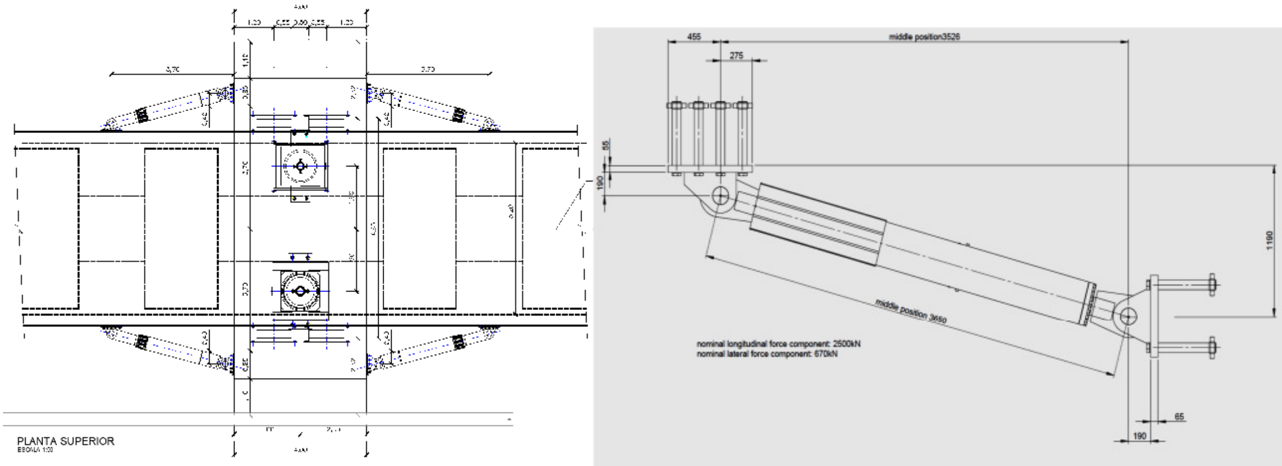

Figure 2 On the left side- Top view on fixed delta pier axis with spherical bearing in centre, re-centring spring rubber bearings and viscous dampers [1]- On the right side- Viscous dampers with support brackets[3]

The compression stiffness results in the range of maximum 3% from the displacement capacity. In case 500mm displacement capacity in mid position is considered the elastic movement of the damper will be max. 15 mm until the design force level gets activated. Thus the stiffness for a 3 000 kN damper is:

K_{AMORT} = 3 000 kN / 15 mm = 200 kN/mm

These devices provide a high grade of energy dissipation when the defined nominal threshold force for fixation and positioning of the deck will be exceeded. The performance was tested full scale at an independent testing institute according to EN15129. For reliability the factor of 1.5, recommended by EN1998, was applied on the displacement capacity of the dampers, i.e. the seismic design displacement was considered to be +/- 450 mm. The total dampers forces of 6-8 nos. single units were chosen to be in the range of 24000 kN to 30000 kN.

The re-centering of the system (Figure 3, on the left) will be provided only on the fixed axes by vertically arranged shear deforming rubber spring isolators. These springs accommodate up to 500 mm by shear deformation while pushing back the deck during and after the earthquake in mid position. The stiffness of each specifically designed set of springs on the fixed axes is 25000 to 32000 kN/m providing approximately 12000 kN maximum re-centering forces to each of the single deck sections. During the construction phase the deck structure cannot be connected to the viscous dampers as the construction method is not enabling this. The longitudinal earthquake movements are controlled exclusively by the elastic re-centering rubber spring isolators.

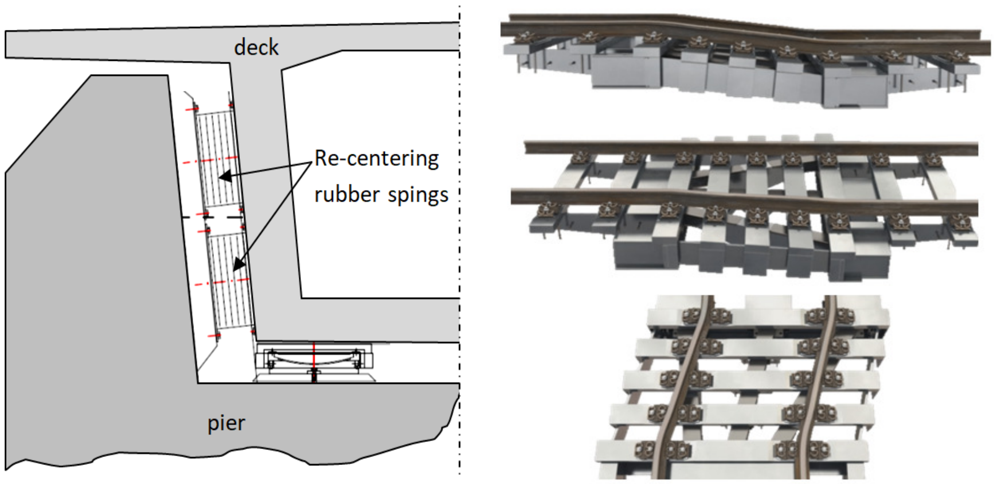

Figure 3 On the left side: Arrangement of re-centering rubber springs on fixed axis between deck an pier top concrete buffers; sample on top of delta pier [4], on the right side: Cross Tie enables longitudinal displacements with lateral, torsional and vertical off-set

The deck is set onto two longitudinally spherical sliding bearings per axis to mitigate seismic accelerations. The load on each bearing is 15 000 kN dead load and 29 000 kN maximum load considering the maximum vertical seismic impacts. During movement the bearing induces very low dynamic friction of 0.5-1% and 1-2% static friction. Together with the re-centering spring isolators and the viscous dampers the deck period has been shifted towards 3s while the total longitudinal base shear is in the range of 10% only. This design philosophy, concentrate the damper and re-centering forces to one fixed axis only, results in a very slender economical structural design. In addition, the applied spherical bearings enable free and unrestrained horizontal rotation capability of up to ±0.02 rad.

Between the single deck sections and at the abutments specific railway expansions joints, called guided Cross Ties, were applied. These special joints compensate creep, shrinkage, thermal and seismic movements of maximum 730 mm without damages to the structure and the rails (Figure 3, on the right).

Lateral system function

The general design philosophy has been to fix the deck in lateral direction and not to allow any seismic or service movements greater than 5-10 mm. One of the two sliding bearings on each pier has got a lateral restrainer guide system to lock lateral displacements while accepting longitudinal ones.

The lateral restrainer has been designed to resist the 9 year return period earthquake during construction phase with up to 5100 kN per pier. After the deck will be finished the lateral concrete buffers will be added. Between these concrete buffers and the deck some sliding rubber bearings will be placed to avoid concrete sliding on concrete. These buffers transmit up to 18000 kN corresponding to the MCE earthquake for 1475 year return period. Thus incase these forces occur the lateral restrainer of the spherical bearings will slightly start to yield by 5-10 mm until the external concrete buffers get activated.

CASE 2: SEISMIC ISOLATION OF ESKISEHIR HOSPITAL IN TURKEY

INTRODUCTION

In Turkey several new hospitals have been built during the past years. One of these is the Eskişehir City Hospital (Figure 4 Animation of Eskişehir City Hospital issued by DOST Constructionn (Figure 4) with 1081 nos. beds in the Odunpazari District of Eskişehir 250 km south east of Istanbul. Due to the high seismicity of this region with up to 0.6 g PGA the published standard [5] by Ministry of Health (MOH) required to apply seismic isolation for this structure with 977 nos. devices to reduce the base shear on the upper floor levels even down to less than 0.2 g[6]. For seismic isolation it was allowed to apply either friction pendulum devices or lead rubber bearings or high damping rubber bearings. Finally the friction pendulum type of isolator was identified to be technically the best, maintenance-free and even economically the cheapest solution considering the project requirements.

For the isolator design it was allowed to apply ASCE 7-10, EN15129 or IBC 2012 upon approval by the MOH. The entire hospital consists of four single main blocks A, B, C and D (Figure 4) with isolators on the second cellar level.

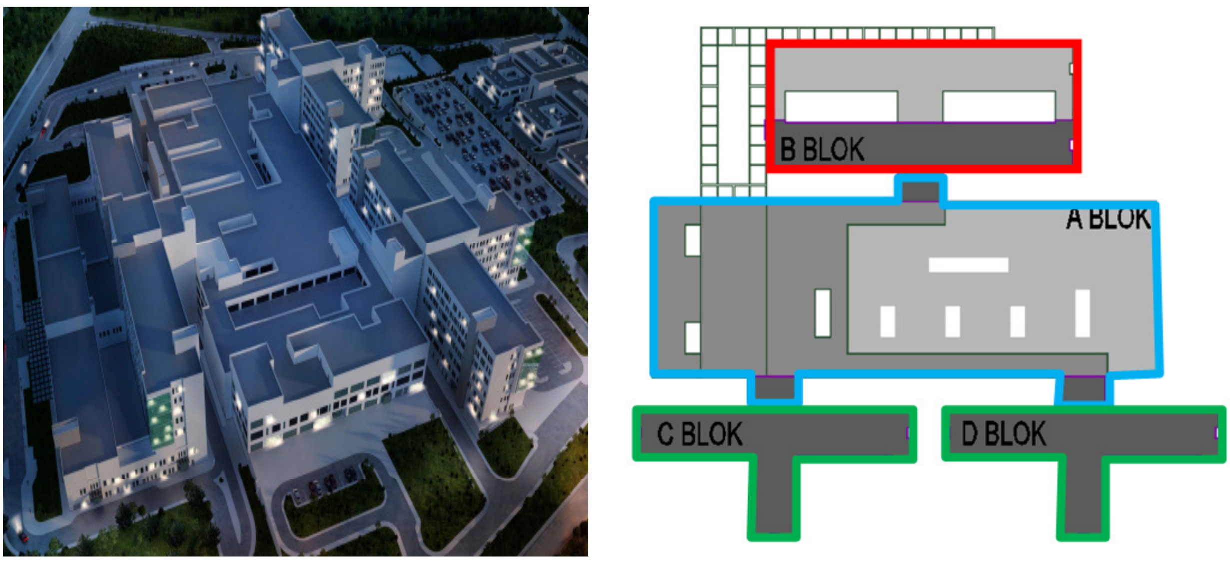

Figure 4 Animation of Eskişehir City Hospital issued by DOST Construction and single blocks of the hospital

Block A has 561 nos. isolators, block B has 216 nos., block C has 100 nos. and block D has 100 nos. [6].

DESIGN of SEISMIC ISOLATION SYSTEM

For the isolation system Sliding Isolation Pendulums with double sliding plate (SIP D), which represent the most recent development stage on the field of friction pendulum systems, were applied.

Seismic hazard analysis

The Odunpazari District of Eskişehir is in 2nd degree seismic zone according to the Turkish Earthquake Code 2007 [7]. The seismic hazard analysis was carried out by SismoLab Engineering in Ankara.

The required horizontal site spectra for the 475 and 2475 years return periods are shown in Figure 5.

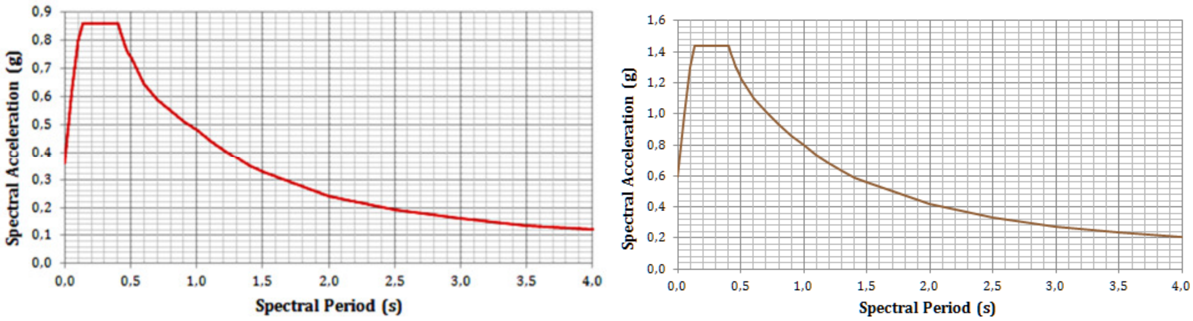

Figure 5 Horizontal specific spectra for 475(on the left) and 2475 (on the right) years return period (5 % damping)

Structural performance demand

To achieve that after the MCE earthquake absolutely no damages within the structure occur, certain demands [6] must be considered.

1. The relative displacement between stores must be less than 0.5 % of height level.
2. The maximum horizontal story acceleration on any floor (!) must be less than 0.2 g.
3. The maximum vertically acting force onto the isolator will be obtained from the load case *1.2 Dead Load + Live Load + Earthquake Load*. The minimum axial force comes from *0.9 Dead Load - Earthquake Load*.
4. Maximum displacement including reliabilities shall be less than 500 mm.
5. Stability and integrity of isolators must be granted!

The above issues must be evaluated and confirmed within a nonlinear time-history seismic analysis of the structure with the applied SIP D devices. The suitable testing of the devices is verifying their stability and integrity even after several seismic events.

Seismic analysis of the structure

To determine suitable isolator characteristics an equivalent linear analysis and a nonlinear time-history analysis was performed.

The property modification factors for the SIP D isolators representing the lower and upper bound performance levels were taken according to previous testing and design experience on similar devices for Isparta City Hospital and Erzurum Medical Campus as follows:

$\lambda_{min} = 1.0$ and $\lambda_{max} = 1.6$

Equivalent linear analysis

Taking into account the response spectra in Figure 5 and the property modification factors, the equivalent damping ratio of the isolation system for the design and partly also for the maximum credible earthquake level exceeded 30 %. Thus it was required according to the code to go for the nonlinear time-history analysis.

Nonlinear time-history analysis

The project specification [6] specified to apply the seismic records of the earthquakes of Imperial Valley (1979), Morgan Hill (1984), Chalfant Valley-02 (1986), Superstition Hill-02, Landers (1992), Kocaeli (1999) and Joshua Tree (1992) (Figure 6) These had to be scaled to the required levels in (Figure 5).

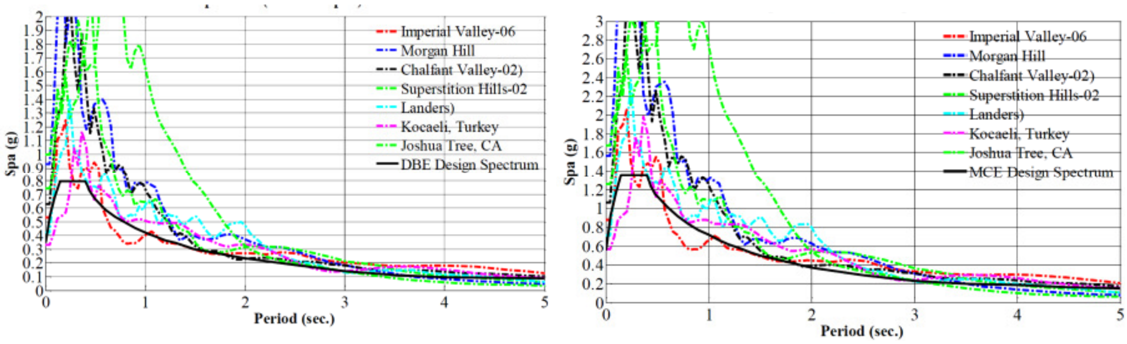

Figure 6 Horizontal pseudo acceleration spectrum (5 % damping) for DBE(on the left) and MCE (on the right)-level ground motion

Together with the provided FE model and the soil data a nonlinear time-history analysis was carried out, while achieving 377 mm maximum displacement for MCE and 177 mm for DBE load case with λ_{min} = 1.0. The max. MCE-base shear at the isolator for λ_{max} = 1.6 is 12.7 % of the structural seismic weight, which was defined to be *Dead Load + 0.3 Live Load* [1]. The DBE-base shear will then be limited to 7.6 % for λ_{max} = 1.6.

Within the structural 3D-FE model of it could be shown that the 0.2 g maximum lateral acceleration was not exceeded on the upper floor levels. Therefore it could be granted with this rather soft isolation system that no structural damages and no damages to the medical equipment will occur. The continued functionality was granted from the structural design side.

DESIGN of the ISOLATORS

For the required loads between 2,500 kN and 25,100 kN in combination with 25 % MCE-damping with +/-377 mm and 37 % DBE-damping with +/-177 mm, the isolation system with lead rubber or even high damping rubber bearings turned out to be not feasible and not economic. Therefore the friction pendulum type with two sliding plates was chosen (Figure 7). The effective period was finally between 2.9 s for DBE and 3.5 s for MCE. These values were requiring 5000 mm effective pendulum radius within the isolator and a nominal dynamic friction of 5 % considering *Dead Load + 0.3 Live Load* [5].

The applied sliding liner material is called MSM®, which is a patented, high-performance sliding material for structural bearings. At the maximum displacement positions the sliding liner edges will be loaded with up to 200 MPa, while not suffering at all. Even after several MCE events none of these SIP D bearings need maintenance or must be exchanged during the life time of the Eskişehir City Hospital [7][8]. The SIP D design, all applied materials and the quality management system are conform to the European Technical Approval (ETA) for spherical structural bearings of MAURER SE [10].

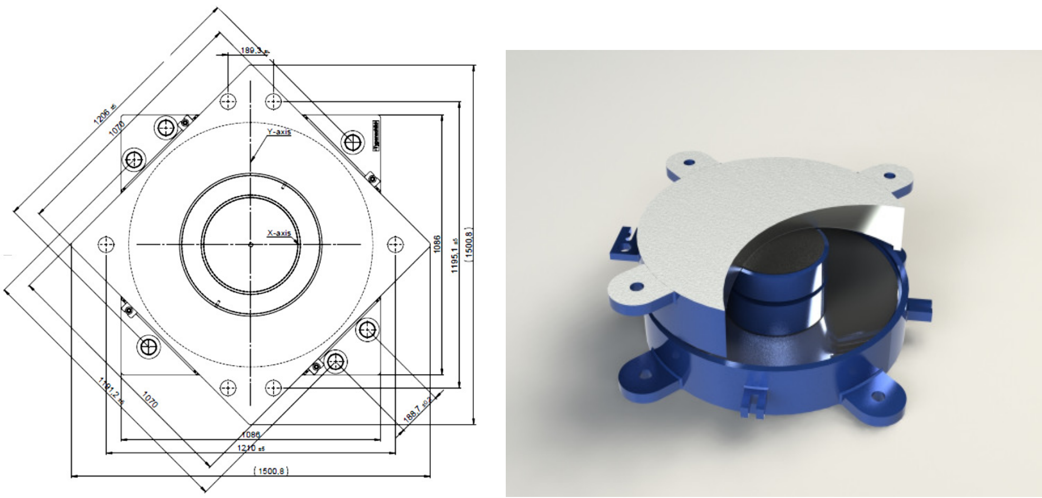

Figure 7 Design of the biggest SIP D isolator

The displacement capability of 377 mm for the lower bound properties of the isolators was increased on demand of the designer by 15 % to 430 mm. These 15 % reliability will cover structural uncertainties like not perfect re-centring.The lateral forces induced by the isolators´ inner friction and stiffness were anchored with 4-6 nos. massive bolted concrete anchor dowels (up to 65 mm diameter and 390 mm length) into the concrete (Figure 7).

TESTING of the ISOLATORS

For testing ASCE 7-10 or EN15129 or IBC 2012 was allowed be applied. The chosen SIP D isolator design is based on the European Technical Approval [10] for spherical bearings and therefore it was most reasonable to perform the testing according to the European standard EN15129.

The participating Universities from Bochum, Munich and Pavia with their high commitment made it possible to test 12 nos. prototypes and 293 nos. production bearings within three months only.

Prototype testing

Two samples of each of the six isolator types – in total 12 nos. - had to be tested. The test matrix of Tab. 1 was applied.

The EU Centre at University Pavia/Italy was chosen for these type tests to fulfil the testing requirements of max. 500 mm/s velocity combined with maximum 430 mm displacement amplitude.

After testing the isolators were opened to determine any degradation or damages to the liner or device itself. No damages were found. There were no signs of wearing, extrusion or scratches in the liner and not on the stainless steel.

The simulation of more than three MCE events on the same SIP D device showed no signs of wearing and the performance characteristics did also not change at all.

The test results have proven the reliability of the isolators´ damping capability during several simulated MCE events. The isolators produced constant hysteretic loops, while showing very low static friction values of 6 to 6.25 %, which have no influence on locking effects for any frequently returning earthquakes.

Table 1 Test matrix for prototype testing for one certain bearing type 1

test #	test name	label	main dof	Ampl. [m]	max vel [m/s]	freq [Hz]	load shape	vert load [kN]	cycles [#]
0	Pre-test 0	P0	long	±0,430	0,500	0,185	sine	2493	3
1	Pre-test 1	PT1	vert	-	-	-	constant	2493	-
2	Frictional Resistance	FR	long	±0,006	0,0001	0,0042	triangular	2493	1
3	Service	S	long	±0,010	0,005	0,080	sine	2493	20
4	Benchmark	P1	long	±0,185	0,050	0,043	sine	2493	3
5	Dynamic 1	D1	long	±0,108	0,500	0,740	sine	2493	3
6	Dynamic 2	D2	long	±0,215	0,500	0,370	sine	2493	3
7	Dynamic 3	D3	long	±0,430	0,500	0,185	sine	2493	3
8	Seismic (N_Ed, max)	E1	long	±0,430	0,500	0,185	sine	7039	3
9	Seismic (N_Ed, min)	E2	long	±0,430	0,500	0,185	sine	1500	3
10	Property verification	P2	long	±0,430	0,500	0,185	sine	2493	3
11	Bi-Directional	B	long	±0,430	0,500	0,185	sine	2493	3
12	Load Bearing Capacity	BC	vert	-	-	-	constant	7039	-
13	Post-test	PT2	vert	-	-	-	constant	2493	-

Therefore it can be concluded that the isolators will work properly during the entire life time of the structure, which 80-120 years for such kind of buildings! The testing criteria had been totally fulfilled.

Production testing

In total 292 nos. – corresponding to 30 % out of all 977 nos. devices – had to be tested within the production test framework. These tests were performed at Universitaet der Bundeswehr in Munich/Germany and Ruhr-Universitaet Bochum/Germany to get 292. nos. device tested just in time. Per day 2 to 5 nos. devices, which were randomly chosen by the construction company, were tested. The testing was performed with the seismic load *Dead Load + 0.3 Live Load* at 50mm/s and for +/-185 mm displacement.

CONCLUSIONS

It has been shown for Toluca-Mexico Project with significant earthquake hazard that it is possible with a combination of available bearings, springs, viscous dampers and expansion joints to decrease service and seismic displacement combination to max. ±450 mm. The forces onto the piers were significantly reduced by up to factor five in longitudinal direction and at the deck section ends any occurring movements were entirely compensated.

After the MCE earthquake with declared 1450 year return period the bridge is still ready to be overpassed and continued functionality is ensured. The proposed system has a service life time of at least 50 years, what was proven by European Technical Approvals for materials and long term dynamic fatigue testing.

For the Eskişehir City Hospital an isolation system consisting of Sliding Isolation Pendulums (SIP D) was chosen, as it deemed to be best in terms of technical performance and economical demands. Within a structural time-history analysis the SIP D performance parameters – like damping and period - were evaluated to be most suitable to fulfil the challenging demand of max. 0.2 g acceleration limit on the upper floor levels.

The isolator design according to the European Technical Approval [10] is ensuring the highest possible quality level. The devices were consequently adapted to the rather great loads of up to 25 MN and the demand for absolute integrity combined with extreme durability even after several MCE events.

The third party testing under severe testing conditions at Universities in Bochum, Munich and Pavia confirmed the performance stability and reliability together with excellent durability.

Based on the perfect isolator performance it could be ensured that maintenance will not be needed. Concluding from this, the service life time will be identical to the building or even longer. The selected SIP D device type is fulfilling together with its selected rather special performance the no-damage-criteria even for the MCE earthquake

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