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Independent Review of the Seismic Safety Peer Review Panel Proposal to Shim the Bearings at Pier E2 of the New East Span of the San Francisco - Oakland Bay Bridge

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Executive Summary

The 2013 Labour Day opening schedule for the new East Span of the San Francisco-Oakland Bay Bridge has been threatened by the premature failure of some anchor bolts in shear connectors S1 and S2 at Pier E2. These bolts are embedded into the crossbeam of Pier E2 and cannot quickly be replaced.

The Seismic Safety Peer Review Panel has proposed to temporarily shim bearings B1, B2 and B3, B4, which respectively are close to shear connectors S1 and S2, thereby converting the bearings into shear connectors offering load paths equivalent to S1 and S2 for the 1500 year return period design seismic event.

Dr. Peter R. Taylor, P.E. of Buckland & Taylor has been invited to conduct this independent review of the engineering analysis and strategy of the "shim concept", which includes opening the new east span to traffic once the bearing shims are installed, before the shear key retrofit is complete.

The review has comprised a one day site visit (which included lengthy discussions with Dr. Brian Maroney, P.E., Toll Bridge Seismic Retrofit Program Chief Bridge Engineer, James Duxbury, P.E., Senior Associate of the Design Team of T.Y. Lin – Moffatt & Nicol and a number of other members of the Owners Design and Construction Staff), a review of the Report on the bolt failures[1] and the Report on the Seismic Evaluation of Pier E2[2] and other documents plus exchanges of written questions and answers.

In order to fully understand the evolving seismic load path, the four successive stages of seismic connectivity at Pier E2 were identified and are reported in Section 4 of this review document. The capacities and functions of the critical elements were then calibrated against the seismic strength and performance demands, permitting conclusions to be drawn regarding the validity of the shim concept.

Strategic decisions taken early in the design phase of the project, such as designing for 140% of the maximum seismic demand at this key support, and creating the seismic connectivity through a family of eight redundant connections, created a favourable environment permitting consideration of temporary alternative load paths around a problem area, such as proposed by the shim concept. Consequently, this simple intervention is able to create alternative temporary load paths with seismic load transmission capacity in excess of the 1500 year return period seismic demands. The shim concept is simple, effective, economical and without any significant impairments to the seismic performance of the bridge.

The Seismic Safety Peer Review Panel is to be congratulated for identifying this effective strategy.

It is recommended that the shim concept be installed at the earliest opportunity because it restores "as designed" seismic capacity at Pier E2 and will provide appropriate interim seismic protection to users of the new bridge when it is opened.

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1 Scope of Work

The Scope of Work for this independent review has been defined as follows.

The Consultant shall conduct an independent review of the Seismic Safety Peer Review Panel proposal to shim the bearings at Pier E2 of the new east span of the San Francisco-Oakland Bay Bridge (SFOBB). Technical materials related to the bearing shims will be provided by BATA for the independent review of the engineering analysis and strategy for this proposal.

This bearing shim proposal includes opening the new east span to traffic once the bearing shims are installed, but before the shear key retrofit is complete. This proposal intends to temporarily restore shear capacity lost due to the failed bolts used to clamp down two shear keys on Pier E2. The bearings were designed to accommodate 20 mm of movement before engaging during a seismic event. The shims would lock the four bearings to engage simultaneously with the two remaining shear keys that are currently in place on the cross beam and functioning as designed.

Since the bearing shim proposal may offer the possibility of achieving seismic safety on the SFOBB prior to completion of the shear key retrofit, time is of the essence in the completion of the Consultant’s review. The Consultant shall contact the BATA Project Manager if any additional information is required to conduct the review.

The services to be performed by Consultant shall consist of services requested by the Project Manager or a designated representative including, but not limited to, the following:

1.1 Task 1

Consultant shall provide an independent review of the engineering analysis and strategy as related to the proposal to shim the existing bearings at Pier E2 to achieve the seismic design requirements of the new east span of the San Francisco-Oakland Bay Bridge.

Consultant shall conduct a peer review of the suitability of the “Shim Concept” to provide sufficient seismic capacity at Pier E2 of the San Francisco-Oakland Bay Bridge to withstand the Safety Earthquake Event (SEE) forces until the shear keys are repaired. In performing the work, Consultant shall use:

i. Load demands at pier E2 from the analysis of the SEE pushover by the Engineer of Record (EOR) as summarized in “Seismic Evaluation of SAS at E2 Bent Prior to Completion of Shear Keys S1 and S2” dated July 15, 2013;

ii. Details of bearings, shear keys and cap beam at Pier E2 and the supports of shear keys and bearings in the orthotropic box girders provided by EOR; and

iii. Other calculations, plan sheets, shop drawings and engineering summaries prepared or supplied by request to the EOR as may be needed.

The zone of the SFOBB to be considered is the load at Pier E2 from the box girder bearing and shear key supports to the tops of the columns.

The following is expressly not included:

i. Review of the failures of the 2008 anchor bolts;

ii. Independent seismic analysis or evaluation other than force transfer in the zone identified above;

iii. Any capacity of the box girders or the substructure other than the force transfer zone identified above;

iv. Any evaluation of the repair of the shear keys (S1 and S2) or the resulting suitability;

v. Any evaluation of the original design of the cap beam at Pier E2 other than as may be needed to evaluate the changes to the load path caused by the temporary shimming; and

vi. Any other function of the shear keys and bearings other than transferring seismic demands in the temporary shimmed condition.

1.2 Deliverable

Independent review report.

2 Introduction

The proposal by the Seismic Safety Peer Review Panel to temporarily shim the bearings at Pier E2 appears, on initial inspection, to provide a simple, easily executed fix, which temporarily avoids reliance on the compromised shear keys S1 and S2 by utilizing an alternate load path through bearings B1, B2, B3, B4 to transmit the required proportion of the major seismic shear demands at that pier.

However, there is a readily understood tendency among engineers evaluating an unconventional way around an unexpected roadblock to see only the advantages of the detour strategy. Therefore, this report is structured to carefully look at how the seismic loads are transmitted in each of the steps in the four stages of development of the final revised design configuration at Pier E2 in order to detect if anything has been overlooked in this sequence.

These stages are:

i. the “as originally designed” seismic connection at Pier E2;

ii. the “current” seismic connection at Pier E2;

iii. the “proposed temporary” seismic connection at Pier E2; and

iv. the “revised final design” seismic connection at Pier E2.

This stage review permits the development of a familiarity with the load paths and details of the proposed “fix” and the varying functions of the key components.

The demands and capacities in the key components in stage iii are then reviewed prior to drawing conclusions about the overall strategy.

3 Global Seismic Demands at Pier E2

In accordance with the Seismic Demands for the Design Level Earthquake per the Project Specific Design Criteria, an envelope of the maximum time-history analysis responses from six different 1500-year ground motions (Safety Evaluation Earthquake) was derived. At the top of Pier E2, these Safety Evaluation Earthquake envelope demands are 50 MN in the longitudinal direction of the bridge and 120 MN in the transverse direction of the bridge.

4 Review of the Transmission of Horizontal Seismic Forces from the Bridge Superstructure into Pier E2 for Each of the Four Stages of Design Development of the Seismic Connections

4.1 Stage 1: Transmission of Horizontal Seismic Forces from the Bridge Superstructure into Pier E2, “As Originally Designed”

The design horizontal capacity of the shear keys and bearings at Pier E2 can be summarized as follows:

Table 1:

	Longitudinal Direction	Transverse Direction
Shear Keys S1 & S2	42 MN each	42 MN each
Shear Keys S3 & S4	42 MN each (20 mm Gap)	42 MN each
Bearings B1, B2, B3 & B4	15 MN each (20 mm Gap)	30 MN each (20 mm Gap)
Maximum Seismic Displacement	1.1 m*	0.4 m*
Total Required Capacity	50 MN	120 MN
Total Capacity Supplied	84 MN	168 MN

* Source: M. Nader 2013 August 07

The “as designed” transmission of horizontal seismic forces at Pier E2 is shown in Figure 1.

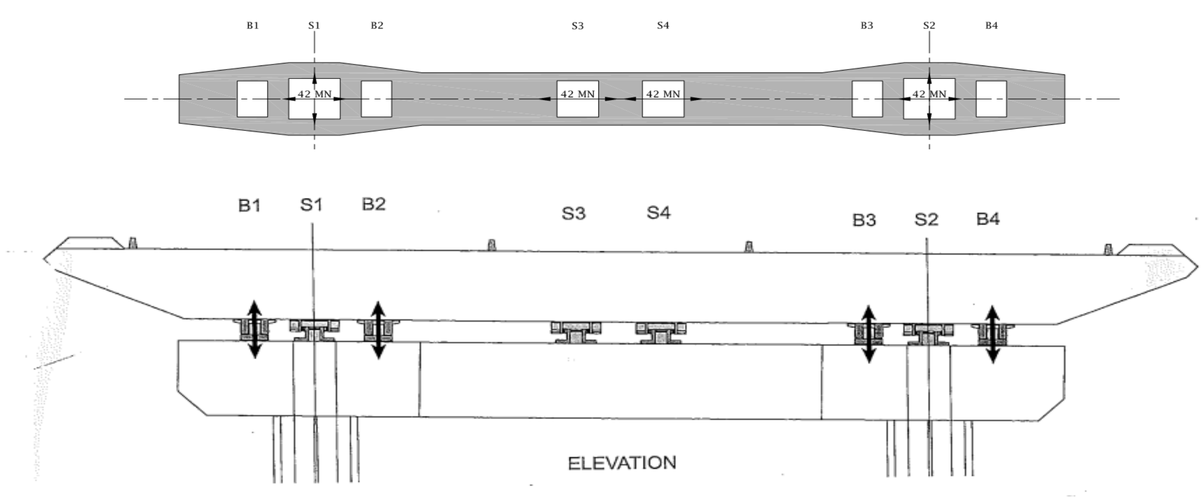

Figure 1: “As Designed” Transmission of Horizontal Seismic Forces at Pier E2

The design seismic load paths maintain the 20 mm longitudinal gaps in shear keys S3 and S4 and the 20 mm longitudinal and lateral gaps in Bearings B1, B2, B3 and B4, thereby engaging only shear keys S1 and S2 in both directions and shear keys S3 and S4 in the transverse direction. This provides a total seismic horizontal connection capacity of 84 MN longitudinally and 168 MN in the transverse direction.

The horizontal seismic demand on the shear key bases at Bent E2 comprises both shear and moment, which are resisted by the friction (coefficient 0.67) and clamping forces created by 48 bolts of 3 inch diameter (ASTM A354 Grade BD) pretensioned to 68% of their ultimate stress of 140 ksi (965 MPa) or about 3 MN per bolt.

The equivalent demand between the shear key top sections and the steel box superstructure at Pier E2 is resisted by the friction (coefficient 0.50) and clamping forces created by 80 bolts of the same diameter and pretension.

The lack of transverse clearances at the shear keys will cause some minor thermal stressing of the top beam of bent E2 and the transverse beam connecting the box girders for temperature differentials between superstructure and bent.

4.2 Stage 2: Transmission of Horizontal Seismic Forces from the Bridge Superstructure into Pier E2 under "Current Conditions"

All of the details of the "current" situation at Pier E2 are not precisely known, but it is known that at shear keys S1, S2 all existing unbroken ASTM A354 Grade BD anchor bolts have had their pretension tensile stress reduced to 0.45 f_u and the two outer longitudinal rows of anchor bolts on the bases have been detensioned and cut flush with the top of baseplate to permit installation of the steel post tension saddles.

In addition, the two temporary bearings used during erection are still in place on the crossbeam of Pier E2 (any contribution from these bearings is ignored in this discussion).

After discounting the broken anchor bolts and those removed in the saddle zone, shear key S1 has 12 functional anchor bolts out of an original 48 and S2 has 16. These anchor bolts are tensioned to 0.45 f_u instead of 0.68 f_u. By proportion, the approximate horizontal load capacity of these shear keys has been reduced to:

S1 $$42 \text{x} \frac{12}{48} \text{x} \frac{0.45}{0.68} = 7\text{MN} \qquad \text{[Eq. 1]}$$

S2 $$42 \text{x} \frac{16}{48} \text{x} \frac{0.45}{0.68} = 9\text{MN} \qquad \text{[Eq. 2]}$$

The anchor bolts at shear keys S3, S4 are from a separate lot from those at S1, S2 and have been tensioned to 0.7 f_u since April (communication from Peter Lee of MTC 2013 August 7.)

The "present" horizontal load capacity of the shear keys and bearings at Pier E2 can be summarized as follows:

Table 2:

	Longitudinal Direction	Transverse Direction
Shear Key S1	7 MN	7 MN
Shear Key S2	9 MN	9 MN
Shear Keys S3, S4	42 MN each (20 mm Gap)	42 MN each
Bearings B1, B2, B3, B4	15 MN each (20 mm Gap)	30 MN each (20 mm Gap)
Total Required Capacity	50 MN	120 MN
Total Capacity Supplied	16 MN	100 MN

The "present" transmission of horizontal seismic forces at Pier E2 is shown in Figure 2.

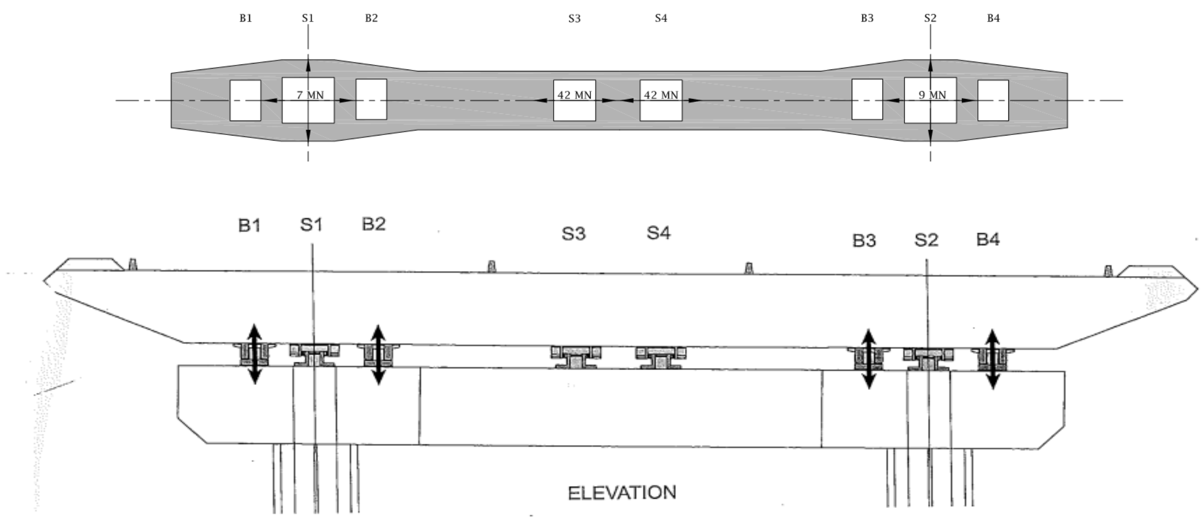

Figure 2: "Present" Transmission of Horizontal Seismic Forces at Pier E2

The "present" configuration of bearings and shear keys at site is unable to mobilize sufficient longitudinal and transverse resistance to handle the demands of the 1500 year ground motions.

4.3 Stage 3: Transmission of Horizontal Seismic Forces from the Bridge Superstructure into Pier E2 under "Proposed Temporary" Conditions

The "proposed temporary" conditions comprise shimming of bearings B1, B2, B3, B4 to eliminate their existing 20 mm longitudinal and transverse bearing travel gaps.

The transmission of horizontal seismic forces would then take place through the four bearings B1, B2, B3, B4 and the two shear keys S3, S4. The small contributions of shear keys S1, S2 during these proposed temporary conditions can be neglected.

The "proposed temporary" horizontal load capacity of the shear keys and bearings at Pier E2 can be summarized as follows:

Table 3:

	Longitudinal Direction	Transverse Direction
Shear Key S1	7 MN (Negligible)	7 MN (Negligible)
Shear Key S2	9 MN (Negligible)	9 MN (Negligible)
Shear Keys S3, S4	42 MN each (20 mm Gap)	42 MN each
Bearings B1, B2, B3, B4	15 MN each	30 MN each
Total Required Capacity	50 MN	120 MN
Total Capacity Supplied	60 MN	204 MN

The "proposed temporary" transmission of horizontal seismic forces at Pier E2 is shown in Figure 3.

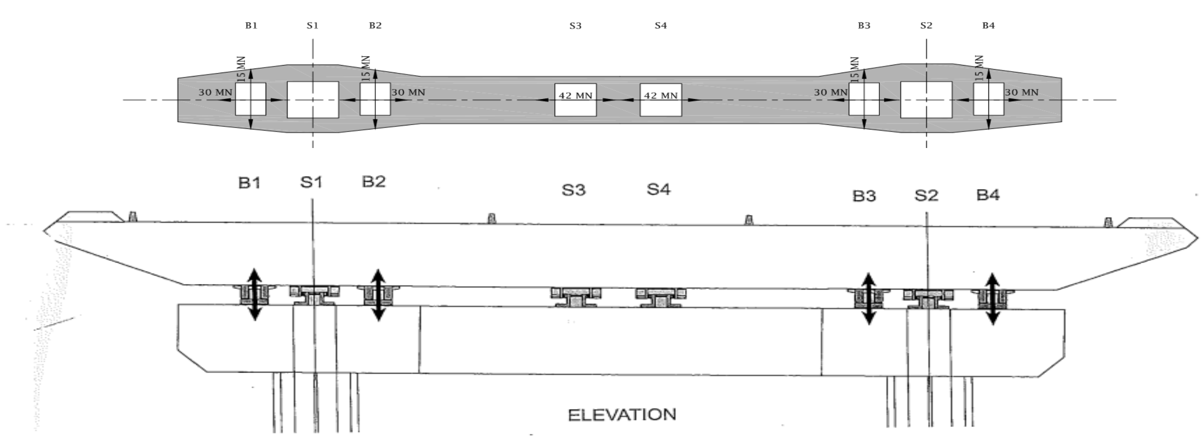

Figure 3: "Proposed Temporary" Transmission of Horizontal Seismic Forces at Pier E2

The “proposed temporary” combined horizontal load capacities of the bearings and shear keys at Pier E2 exceed the seismic demands in both the longitudinal and lateral directions.

The precise distribution of the horizontal forces in the transverse direction between the bearings and shear keys is indeterminate. However, the overall demand over capacity ratio in the transverse direction is only about 0.6, so that significant variations above the average demand on any one component can be tolerated.

Some small thermal forces may occur in the crossbeams of the pier and superstructure at Pier E2 due to differential temperatures between the superstructure and substructure.

4.4 Stage 4: Transmission of Horizontal Seismic Forces from the Bridge Superstructure into Pier E2 under “Revised Final Design” Conditions

The “revised final design” capacities and load paths replicate the “as originally designed” stage, except that the actions of the anchor bolts connecting the bases of shear keys S1 and S2 to the crossbeam of Pier E2 are replaced by a new array of post-tensioned cables anchored on the faces of the Pier E2 crossbeam and pulling downwards on steel yokes located over the shear key baseplates; see Figure 4.

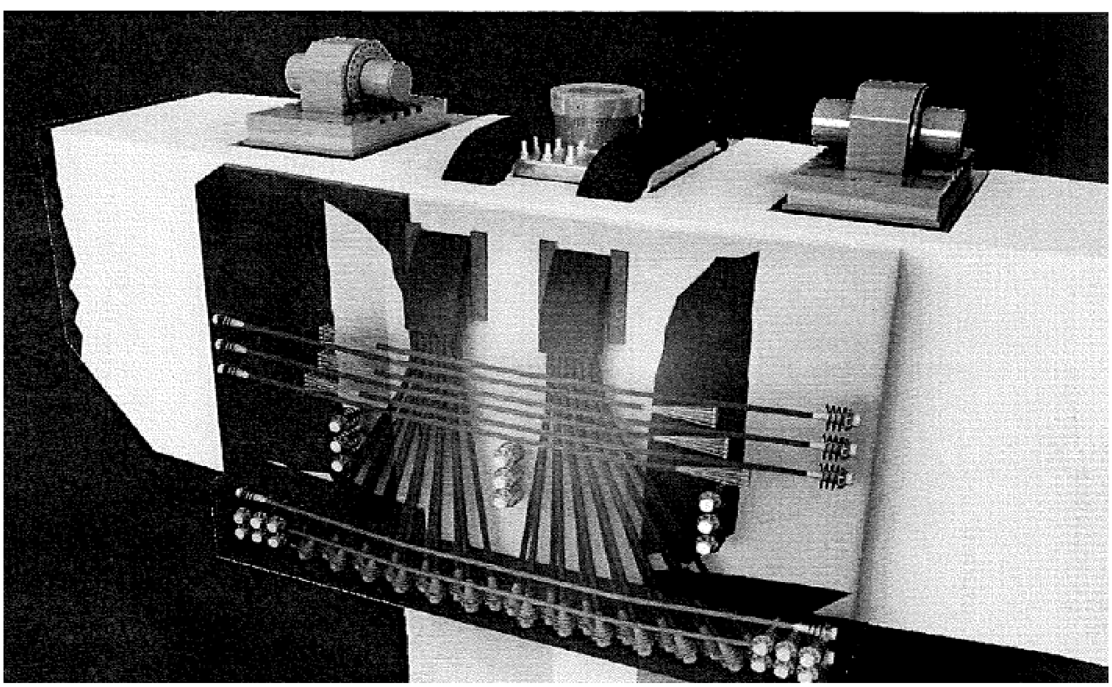

Figure 4: Steel Saddle Retrofit of Shear Keys S1, S2

Once these post-tensioned steel saddle retrofits have been completed at shear keys S1 and S2, then the shims will be removed from bearings B1, B2, B3 and B4.

The “revised final design” horizontal load capacity of the shear keys and bearings at Pier E2 can then be summarized as follows:

Table 4:

	Longitudinal Direction	**Transverse Direction**
Shear Keys S1 & S2	42 MN each	42 MN each
Shear Keys S3 & S4	42 MN each (20 mm Gap)	42 MN each
Bearings B1, B2, B3 & B4	15 MN each (20 mm Gap)	30 MN each (20 mm Gap)
Maximum Seismic Displacement	1.1 m	0.4 m
Total Required Capacity	50 MN	120 MN
Total Capacity Supplied	84 MN	168 MN

The “revised final design” transmission of horizontal seismic forces at Pier E2 in shown in Figure 5.

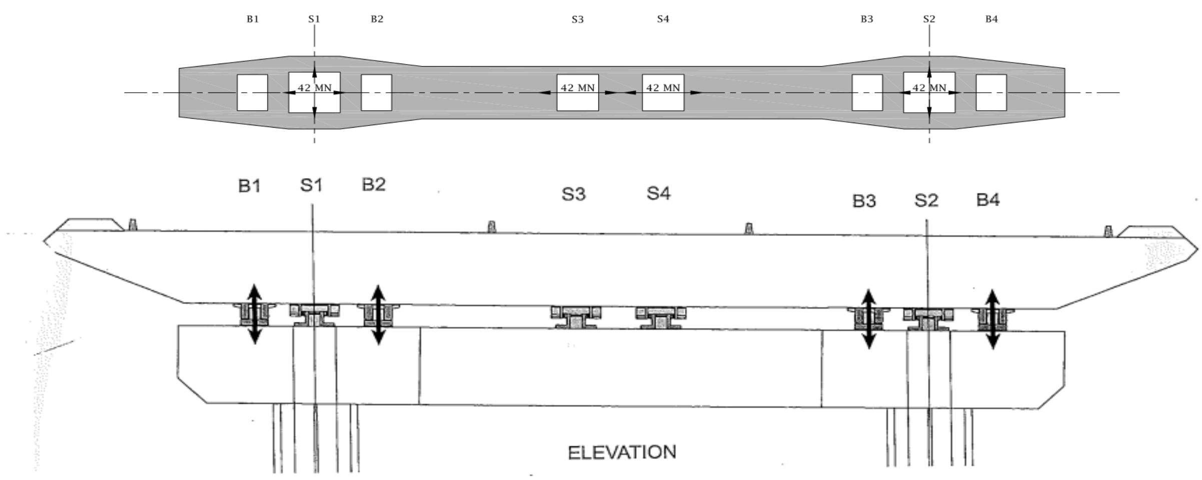

Figure 5: “Revised Final Design” Transmission of Horizontal Seismic Forces at Pier E2

5 Review of the Capacities of Critical Components in the "Proposed Temporary" Conditions

5.1 Shear Keys S3, S4

These components have the largest individual horizontal seismic design load capacity of 42 MN each and in combination with the shimmed bearings bring significant transverse overcapacity to the temporary fix.

During the temporary conditions Shear Keys S3, S4 are working together with Bearings B1, B2, B3, B4 to resist transverse seismic loads and the overall transverse demand is only 60% of the capacity, so the shear keys are in general working below their design capacity. The precise transverse load sharing between shear keys S3, S4 and bearings B1, B2, B3, B4 is indeterminate.

The S3, S4 shear key anchor bolts are a different lot from those which failed at shear keys S1 and S2 and have been tensioned to 0.7 f_u since 2013 April. Based on the findings of the Report on the anchor bolts[1], their short term vulnerability to stress corrosion cracking is low. The bolts are scheduled to be replaced after the bridge opening.

5.2 Bearings B1, B2, B3, B4

During temporary conditions the bearings and shear keys combined are working at 83% of design capacity in the longitudinal direction and 60% of design capacity in the transverse direction to resist 1500 years seismic design forces.

The Finite Element Analyses under full design loads presented by the designer[2] show low stresses in the bearings under longitudinal loads and only a few local stress concentrations under transverse loads.

The bearing hold-down analysis uses a coefficient of friction of 0.67 between steel and concrete based on the clamping force achieved with anchor bolts tensioned to 0.70 f_u. Localized yielding occurs at the edges of the bearing lower housing under maximum design transverse seismic loads. This localized yielding may be a result of computer modeling limitations. The amplitude and extent of the yielding is not of concern. As for the shear keys S3, S4, the total transverse load demand available under temporary conditions is only 60% of capacity.

5.3 Shims

Taking into account the local high steel-to-steel bearing stresses identified in the Finite Element Analyses of transverse loadings on the bearings, the shim plates may experience yield strains in a seismic event. The use of high yield strength shim material should be considered.

6 Conclusions

6.1 General Structural Conclusions

It is concluded that introducing shims into bearings B1, B2, B3, B4 at Pier E2 to inhibit their designed longitudinal and transverse bearing travels of 20 mm will create stiff load paths which will temporarily replace the adjacent stiff load paths for horizontal seismic loads through shear connectors S1 and S2, while the latter are rehabilitated.

The new load paths do not affect global seismic stiffnesses, seismic forces or displacement demands.

The new load paths do not affect the strength of Pier E2.

All design provisions to resist uplift at Pier E2 are preserved.

6.2 Specific Component Conclusions

During the temporary conditions, the transverse seismic loads of 120 MN from the superstructure are transmitted to Pier E2 through shear keys S3, S4 and bearings B1, B2, B3, B4 which together have a transverse design capacity of 204 MN. Thus global demands are significantly less than design capacities.

The corresponding proportion of the design capacity utilized in the longitudinal direction is 83% with all of the longitudinal resistance originating in bearings B1, B2, B3, B4.

The “shear key failed” Finite Element Analyses of the bearing components show only minor local zones of high stress under full transverse and longitudinal design load.

We conclude that the bearings and shear keys are well able to handle the 1500 year seismic demands with the bearings in their shimmed configuration during the “proposed temporary conditions”.

The anchor bolts at both the bases and the tops of the shear keys S3, S4 and bearings B1, B2, B3, B4 are of different lots from those that failed at shear keys S1, S2. They have sustained axial stresses of 0.7 f_u since 2013 April and can be considered, in the short term, not to be vulnerable to stress corrosion cracking. They are scheduled to be replaced in the medium term.

7 Recommendation

It is recommended that the shim concept be installed at the earliest opportunity because it restores “as designed” seismic capacity at Pier E2 and will provide appropriate interim seismic protection to users of the new bridge when it is opened.

8 References

[1] Report on the A354 Grade BD High Strength Steel Rods on the New East Span of the San Francisco-Oakland Bay Bridge – with Findings and Decisions; Toll Bridge Program Oversight Committee.

[2] San Francisco-Oakland Bay Bridge Self-Anchored Suspension Span – Seismic Evaluation of SAS at E2 Pier prior to completion of shear keys S1 & S2 July 15, 2013 T.Y. Lin – Moffatt & Nichol.