Toll Bridge Program Oversight Committee
Department of Transportation
Office of the Director
1120 N Street
P.O. Box 942873
Sacramento, CA 94273-0001

July 12, 2013

Mr. Vincent Mammano
California Division Administrator
Federal Highway Administration
650 Capitol Mall, Suite 4-100
Sacramento, CA 95814

RE: SFOBB Bearing Shims

Dear Mr. Mammano,

The Toll Bridge Program Oversight Committee (TBPOC) requests further assistance from the Federal Highway Administration to 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). This proposal would open the new span to traffic once the bearing shims are installed, but before the shear key retrofit is complete.

The proposal would 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 laterally before engaging during a seismic event. The shims would lock the four bearings laterally to engage simultaneously with the two remaining shear keys that are currently in place on the cross beam and functioning as designed.

I am attaching preliminary technical materials related to the bearing shims and asking your team to provide an independent review of the engineering analysis and strategy for this proposal. The TBPOC expects to receive more complete engineering analysis early next week; we will forward more detailed materials to you at that time. If you require any additional information to conduct your review, please contact me as soon as possible. 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 your review.

Thank you for your continued assistance and cooperation in ensuring that we open a safe new bridge for the traveling public at the earliest responsible date.

Sincerely,

Steve Heminger
Chair, TBPOC

Attachments
cc: Malcolm Dougherty, Caltrans
    Andre Boutros, CTC
    Brian Kelly, Transportation Agency
San Francisco-Oakland Bay Bridge
Self-Anchored Suspension Span (SFOBB-SAS)

SEISMIC EVALUATION OF SAS AT E2 PIER PRIOR TO COMPLETION OF SHEAR KEYS S1 & S2

July 15, 2013
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<td>97</td>
</tr>
</tbody>
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STATEMENT OF PURPOSE:

This report provides a summary of the technical information for the seismic evaluations of the San Francisco-Oakland Bay Bridge (SFOBB) East Spans Self-Anchored Suspension (SAS) at E2 Pier prior to completion of shear keys S1 and S2.

This report documents information on demand and capacity of relevant stages of construction and service. Additionally, visual images are included to support the understanding of various structural elements and staging. Supporting finite element analysis (FEM) is also provided.

This report evaluates temporary bearing modifications by adding simple shims to the Pier E2 Bearings (B1, B2, B3 and B4) to engage the bearing’s reserve capacities for an interim condition.
EXECUTIVE SUMMARY:

As requested by Caltrans and as presented and discussed during the Seismic Safety Peer Review Panel (SSPRP) meeting with Caltrans and the peer review panel on July 3 2013, the Design Joint Venture of T.Y. Lin International / Moffatt & Nichol Engineers have performed an evaluation of the seismic capacity of the shear keys and bearings at Pier E2 of the Self-Anchored Suspension (SAS) Bridge. To this end various alternative load paths were evaluated and compared against the Seismic Demands for the Design Level Earthquake per the Project Specific Design Criteria. These Seismic Demands correspond to the envelope of the maximum time-history analysis response from six different 1500-year ground motions (SEE - Safety Evaluation Earthquake). At the top of Pier E2, these SEE demands total 50MN in the longitudinal direction of the bridge and 120MN in the transverse direction of the bridge.

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

<table>
<thead>
<tr>
<th></th>
<th>Longitudinal Direction</th>
<th>Transverse Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Shear Keys S1 &amp; S2:</td>
<td>42 MN</td>
<td>42 MN</td>
</tr>
<tr>
<td>- Shear Keys S3 &amp; S4:</td>
<td>42 MN (20mm Gap)</td>
<td>42 MN</td>
</tr>
<tr>
<td>- Bearings B1, B2, B3 &amp; B4:</td>
<td>15 MN (20 mm Gap)</td>
<td>30 MN (20 mm Gap)</td>
</tr>
</tbody>
</table>

The design plans account for two alternative load paths:

A) Load Path A (shear keys are engaged) – This load path maintains the 20 mm gaps in S3 & S4 and the Bearings B1, B2, B3 & B4, thereby engaging only shear keys S1 & S2 in both directions and S3 & S4 in the transverse direction only. This provides a total capacity of 84 MN and 168 MN in the longitudinal and transverse directions, respectively.

B) Load Path B (all shear keys discounted) – This load path engages the Bearings B1, B2, B3 & B4 in both directions upon closing of the 20 mm gap due to seismic movement. This provides a total capacity of 60 MN and 120 MN in the longitudinal and transverse directions, respectively.

Assuming that the New Design of the Shear Keys S1 & S2 is not completed and by implementing interim shimming of the Bearings B1, B2, B3 & B4 to close the 20 mm gaps, a third alternative load path to resist the design lateral SEE demands can be developed: (reference Plan Sheet 883S1/1204 “Pier E2 Details No. 1A”)

C) Load Path C (shear keys S1 & S2 discounted) – This load path engages the Bearings B1, B2, B3 & B4 by interim shimming of the 20 mm gaps in both directions, in addition to S3 & S4 being engaged in the transverse direction only. This provides a total capacity of 60 MN and 204 MN in the longitudinal and transverse directions, respectively.

The table in the Evaluation of Alternative Load Path at Pier E2 section provides a summary of the Seismic Lateral Capacity at Pier E2 for Load Path A, B & C, the SEE demands, and the associated Factors of Safety.
Enclosed please find a rendering depicting the installation sequence of the shims as well as a Finite Element Analysis (FEM) of the bearings.
BRIAN MARONEY’S (CALTRANS) MEMO:

(FROM EMAIL DATED JUNE 29, 2013 TO PMT / TBPOC / SSPRP)

This memo is to briefly summarize the safety of the Self-Anchored-Suspension bridge segment with respect to the expected performance of the San Francisco-Oakland Bay Bridge during a design level earthquake assuming the S1 and S2 shear key work currently underway is not fully completed by the time of seismic safety opening. In simplified terms, the bridge system between the orthotropic box girder superstructure and the concrete Pier E2 bentcap has enough strength capacity to carry 1500 year return period design level earthquake motion generated shear forces, overwhelmingly driving a shift of public traffic to the replacement bridge from the old bridge based on a desire for public safety.

The bridge capacity to carry the demand loads at Pier E2 is overdesigned to 140% of the worst of six different 1500 year return period earthquake time-history generated loads. The design criteria of the East Spans of the Bay Bridge is based upon 1500 year return period motions, which excides the national standards of 1000 year return period motions. This can be read as there is a 40% extra capacity in the “as-designed” system at Pier E2 above the lifeline criteria that is above the national standard. In simple terms, the system at Pier E2 was not designed to the bare minimum and there was a significant reserve capacity incorporated into the design that we should recognize at this time as leaders consider opening day alternatives. This extra design reserve is important to recognize when accounting for the fact that in construction there has developed a temporary reduction in capacity due to the Pier E2 threaded rod problem. The temporary reduction in strength capacity of the Pier E2 system due to the 2008 rod fractures is less than the overdesign. Therefore, leadership can advance increase public safety by opening the bridge as soon as feasible.

From bridge computer demand analysis models, earthquake lateral demands at the top of Pier E2 can be very simply summarized as 120 MN of force transversely and 50 MN of force longitudinally. If it is conservatively assumed that the S1 and S2 shear keys are completely ineffective, the S3 and S4 shear keys are only effective in the transverse direction and the B1, B2, B3 and B4 bearings are temporarily shimmed to engage them at zero relative displacement, lateral capacity to carry the 120 MN lateral demand is estimated at [ 2 * (42) + 4 * (30) ] = 204 MN. Clearly, 204 MN is greater than 120 MN. Similarly, in the longitudinal direction the four shimmed bearings provide a capacity of [ 4 * (15) ] = 60 MN and 60 MN is greater than 50 MN. These simple calculations demonstrate the new bridge provides well-above standard seismic safety even if the S1 and S2 shear key work is not complete.

The existing bridge was not designed for the most basic “no-collapse” seismic safety criteria that is typically employed in modern bridge design. The old bridge is at risk in large Bay Area earthquakes as was demonstrated during the 1989 Loma Prieta Earthquake. The modest interim retrofit was developed to address the most fundamental seismic risks up to a limit of 25 million dollars. It was a good investment but was never intended to address long-term seismic risks associated with even a standard of 1000 year return period “no-collapse” criteria.
This summarizing discussion demonstrates that the San Francisco – Oakland Bay Bridge East Spans Replacement Structure offers significantly superior seismic safety to the public compared to the old bridge. From a technical perspective, it can be relatively easily concluded that the public should be moved onto the new structure at the first practical opportunity even if the S1 and S2 shear key work is not complete. It should be clear that the S1-S2 work is valuable as it provides the level of extra safety, reliability and toughness that was envisioned in the original design by bridge earthquake specialists and should be completed on an expedited schedule.
Evaluation of Alternative Load Path at Pier E2
### EVALUATION OF ALTERNATIVE LOAD PATHS AT PIER E2 FOR SEISMIC RESISTANCE

#### SEISMIC DEMAND FOR SEISMIC SAFETY EVALUATION (SEE EARTHQUAKE)

<table>
<thead>
<tr>
<th>Direction</th>
<th>B1</th>
<th>S1</th>
<th>B2</th>
<th>S3</th>
<th>S4</th>
<th>B3</th>
<th>S2</th>
<th>B4</th>
<th>TOTAL (MN)</th>
<th>SAFETY FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long</td>
<td></td>
<td>42</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15</td>
<td></td>
<td>15</td>
<td>60</td>
</tr>
<tr>
<td>Trans</td>
<td></td>
<td>42</td>
<td></td>
<td>42</td>
<td></td>
<td></td>
<td>30</td>
<td></td>
<td>30</td>
<td>120</td>
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</table>

#### LOAD PATH A: (ALL SHEAR KEYS ENGAGED)

<table>
<thead>
<tr>
<th>Direction</th>
<th>B1</th>
<th>S1</th>
<th>B2</th>
<th>S3</th>
<th>S4</th>
<th>B3</th>
<th>S2</th>
<th>B4</th>
<th>TOTAL (MN)</th>
<th>SAFETY FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long</td>
<td></td>
<td>42</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>84</td>
<td>168%</td>
</tr>
<tr>
<td>Trans</td>
<td></td>
<td>42</td>
<td></td>
<td>42</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>168</td>
<td>140%</td>
</tr>
</tbody>
</table>

#### LOAD PATH B: (ALL SHEAR KEYS DISCOUNTED) (BEARINGS ENGAGED)

<table>
<thead>
<tr>
<th>Direction</th>
<th>B1</th>
<th>S1</th>
<th>B2</th>
<th>S3</th>
<th>S4</th>
<th>B3</th>
<th>S2</th>
<th>B4</th>
<th>TOTAL (MN)</th>
<th>SAFETY FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long</td>
<td>15</td>
<td>0</td>
<td>15</td>
<td>0</td>
<td>0</td>
<td>15</td>
<td>0</td>
<td>15</td>
<td>60</td>
<td>120%</td>
</tr>
<tr>
<td>Trans</td>
<td>30</td>
<td>C</td>
<td>30</td>
<td>0</td>
<td>0</td>
<td>30</td>
<td>0</td>
<td>30</td>
<td>120</td>
<td>100%</td>
</tr>
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</table>

#### LOAD PATH C: (INTERIM SHIM OF BEARINGS) (S1 & S2 SHEAR KEYS DISCOUNTED)

<table>
<thead>
<tr>
<th>Direction</th>
<th>B1</th>
<th>S1</th>
<th>B2</th>
<th>S3</th>
<th>S4</th>
<th>B3</th>
<th>S2</th>
<th>B4</th>
<th>TOTAL (MN)</th>
<th>SAFETY FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long</td>
<td>15</td>
<td>0</td>
<td>15</td>
<td></td>
<td></td>
<td>15</td>
<td>0</td>
<td>15</td>
<td>60</td>
<td>120%</td>
</tr>
<tr>
<td>Trans</td>
<td>30</td>
<td>0</td>
<td>30</td>
<td>42</td>
<td>42</td>
<td>30</td>
<td>0</td>
<td>30</td>
<td>204</td>
<td>170%</td>
</tr>
</tbody>
</table>

- **a.** 30 mm gap in the longitudinal direction. Bearing (B1, B2, B3, and B4) engage after 30 mm gap is closed by displacement.
- **b.** 20 mm gap in the transverse direction. Bearing (B1, B2, B3, and B4) engage after 20 mm gap is closed by displacement.
- **c.** 43 mm gap filled with neoprene open cell. Shear Keys (S3 and S4) engage in the longitudinal direction after 43 mm gap is closed by displacement.
LOAD PATH A – ALL SHEAR KEYS ENGAGED
(Force Resistance Of Shear Keys And Bearings)
Direction of applied force that element can resist:
- Uplift
- Transverse
- Longitudinal

PLAN

ELEVATION

Shear Key Assembly, Typ
Bearing Assembly, Typ

B1 B2 S1
B3 B4 S2 S3
LOAD PATH B — ALL SHEAR KEYS DISCOUNTED / ALL BEARINGS ENGAGED
(Force Resistance Of Shear Keys And Bearings)

Direction of applied force that element can resist:
- **Uplift**
- **Transverse**
- **Longitudinal**
LOAD PATH C — INTERIM SHIMMING OF BEARINGS / S1 & S2 SHEAR KEY DISCOUNTED
(Force Resistance Of Shear Keys And Bearings)

Direction of applied force that element can resist:
- Uplift
- Transverse
- Longitudinal
LONGITUDINAL
(DEMANDS & CAPACITIES)

LOAD PATH A
- AS DESIGNED NOMINAL

LOAD PATH B
- AS DESIGNED GAP CLOSED
- S1, S2 DISCOUNTED
- S3, S4 NOT ENGAGED

LOAD PATH C
- INTERIM FIX
- GAP CLOSED BY SHIMMING
- S1, S2 DISCOUNTED
- S3, S4 NOT ENGAGED
Shear key assembly:

\[ M = V \times e_t \]

Shear key housing:

Shear key bushing:

Shear key stub:

Load through shear key:

\[ M = V \times e_b \]
Shear Force = V

M = V \times e_1

BEARING TOP HOUSING

P = \frac{V \times (e_3 - e_2)}{d}

BEARING BOTTOM HOUSING

M = V \times e_3

BEARING HOLD-DOWN ASSEMBLY

LOAD THROUGH BEARING – TRANSVERSE SHEAR
CCO No. 331 – E2 Bearing Shimming Details (883S1 of 1204)
DETAIL OF BEARING ASSEMBLY

INSTALLATION SEQUENCE FOR BEARING SHIMMING:

1. On one OBC (E6 or E8), install longitudinal and transverse shimming on both bearings.
2. On the same OBC and for one temporary bearing at a time, tighten the bolts to the permanent bearing and remove temporary bearing shimming. Repeat for both temporary bearings.
3. Repeat Steps 1 & 2 for the remaining OBCs.

E2 BEARING SHIMMING

NOTES:
1. Shims shall be galvanized.
2. Each shim shall be PEP coated on one side.
3. Provide for each shim pack 4 shims required at 1/40 maximum, as required per survey.
4. Shims shall be within 2 mm. total of all plies.
5. Variable shims shall be fabricated and provided based on field measurements of gaps in the bearing assembly. Cap "D" in the upper housing is 30 mm nominal. Cap "D" in the upper housing is 20 mm nominal.
Shim Installation Sequence
Appendix A - Pier E2 Shear Key and Bearing Design Plans
REVISED PER ADDENDUM NO. 5 DATED DECEMBER 21, 2005

TOWER

1. Transverse slope of concrete cross beam is constant and shall be computed based on the HP elevations of Pier E2 and E2A.
2. For Pier E2 details, see "Pier E2 Details" sheets.
3. For utilities, see "Utility Plans".
4. For drainage, see "Tower Drainage Details" sheets.
5. For interface details between footing and tower base plate, see "Tower Anchorages Details" sheets.
6. Fenders for Pier E2 foundation is part of the Self-Anchored Suspension Bridge (E3 & T1) contract by Others. For tower fender details, see "Tower Fender Details" sheets.
7. For Pier E2 cross beam HP Elevations and slopes, see "Pier E2 Details" sheets.
8. The Contractor shall verify all controlling field dimensions before ordering or fabricating any material.
### Bearing Assembly Table

<table>
<thead>
<tr>
<th>Location</th>
<th>Bearer Type</th>
<th>Number of Bearing Units</th>
<th>Design Load (kN per bearing)</th>
<th>Design Rotation (radial)</th>
<th>Design Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Service Ultimate</td>
<td>Service Ultimate Service Ultimate</td>
<td>Service Ultimate</td>
<td>Service Ultimate</td>
</tr>
<tr>
<td>'N' Line</td>
<td>Spherical Bearing</td>
<td>2</td>
<td>10000 0</td>
<td>86000 0</td>
<td>0.100 0</td>
</tr>
<tr>
<td>'E' Line</td>
<td>Spherical Bearing</td>
<td>2</td>
<td>10000 0</td>
<td>86000 0</td>
<td>0.100 0</td>
</tr>
</tbody>
</table>

** kê: Seismic load factor ≥ 1.5 for shear key engaged load condition, ≤ 1.4.**
** For uplifting only.**

### Shear Key Assembly Table

<table>
<thead>
<tr>
<th>Location</th>
<th>Number of Shear Key Units</th>
<th>Design Load (kN per shear key)</th>
<th>Design Rotation (radial)</th>
<th>Design Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Service Ultimate</td>
<td>Service Ultimate Service Ultimate</td>
<td>Service Ultimate</td>
<td>Service Ultimate</td>
</tr>
<tr>
<td>'N' Line</td>
<td>1</td>
<td>9000 4500 0</td>
<td>42500 3500 0</td>
<td>0.009 0</td>
</tr>
<tr>
<td>'E' Line</td>
<td>1</td>
<td>9000 4500 0</td>
<td>42500 3500 0</td>
<td>0.009 0</td>
</tr>
<tr>
<td>Crossbeam</td>
<td>2</td>
<td>9000 4500 0</td>
<td>42500 3500 0</td>
<td>0.009 0</td>
</tr>
</tbody>
</table>
Spherical Bushing
Assembly Detail

Alternate Bearing Details

Overview of PIER E2 Bearing Details No. 2A

NOTES:
1. For details not shown, see "PIER E2 Bearing Details No. 2" sheet.
2. 35 mm gap £2 mm shall be maintained on both sides during installation.
3. The split plane shall be parallel to the base plate in the final oriented position.
4. Assembly bolts and recesses are shown schematically. Design and details of assembly bolts for spherical housing shall be per bearing manufacturer.
5. Shim plate and PTFE film shall be provided along the 2 sides of the bearing housing in the longitudinal direction of the bridge.
6. Shim plate details may vary with field conditions subject to review and approval of the Engineer.
Appendix B – Bearing Upper Housing

FEM
ANALYSIS OF BEARING UPPER HOUSING FOR
SEISMIC LOADS

Self-Anchored Suspension Bridge
San Francisco Oakland Bay Bridge East Span Seismic Safety Project
Caltrans Project No. 04-0120F4

T.Y. Lin International / Moffatt & Nichol Joint Venture
July 15, 2013
INTRODUCTION

This study investigates the scenario of using only the permanent bearings to resist the seismic safety evaluation earthquake (SEE) load (without shear keys engaged – Load Path B and C).

MODEL

The behavior of the bearing upper housing was evaluated using a finite element model. This model was created using ADINA.

As shown in the figure below, the model includes the following structural components:

1. Bearing upper housing (Pink)
2. OBG base plate (Orange)
3. Bearing anchor bolts (Red vertical lines)
4. Anchor blocks for the bearing anchor bolts (Green)
5. Rigid Shell at the outer boundary of bearing shaft (Blue and Brown)
CONNECTIVITY AND BOUNDARY CONDITIONS

In order to apply the designated loading, the surface of the bearing shaft is modeled with shell elements. The loading To ensure stability of the analysis model, the shell is fully connected to one side (left in the above figure) of the bearing upper housing, through rigid links between the shell and inner face of the bearing housing arm. It is noteworthy that this rigid linked connection is expected to distort the results in the vicinity of the connection locations as an artifact of the modeling that should be discounted. Therefore, the results from the other arm (right) of the bearing housing should be used when applicable. Part of the shell body between the two arms of the bearing upper housing is rigidly connected to the loading point defined per plan, at the CG of the bearing shaft. A coupled contact surface is established between the shell body and the inner face of the other bearing housing arm. The contact surface assumes zero friction to simulate a lubricated interface.

The bearing upper housing is in contact with the bottom face of the OBG base plate. The contact friction coefficient is set to be 0.5, for the designated Class B finish. The upper housing is held to the OBG by A354BD anchor bolts of 3 inch diameter. The anchor bolts are constrained to the bolt holes on both the bearing upper housing and the anchor blocks. The anchor bolts are pretensioned to 0.7fpu under the dead load condition.

For simplicity, the OBG base plate is fully fixed, providing a rigid contact surface for the bearing upper housing. The anchor blocks are also rigidly supported, as they are welded to the OBG frame, which is not fully modeled in this analysis.

LOADS

Bearing forces were extracted from a seismic (time history) analysis of the self-anchored suspension bridge including the bearings and shear keys. The total longitudinal, transverse, and vertical loads transferred from the westbound and eastbound box girders to Pier E2 were extracted from
the analysis and distributed to the bearings and shear keys in accordance with the plans. The bearing loads are shown in Table 1.

Normal functioning of the bearing corresponds to the case “Shear Key Engaged”. The bearing is only required to carry vertical loads. These are either downwards—case C—or upwards—case U. Upwards loads are of greatest concern and are addressed in this report. A “safety factor” of 1.4 is applied to the calculated loads from the seismic analysis.

The bearing is also intended to function as a secondary mechanism to resist longitudinal and transverse loads should the shear keys fail. The three cases of greatest interest are those corresponding to the peak uplift on the bearing (case U), the peak transverse load (case T), and the peak longitudinal load (case L). In each case the orthogonal loads occurring simultaneously with the peak loads are also tabulated (and analyzed). These loads are applied with a “safety factor” of 1.0, since they are based on the conservative assumption that the shear key has failed.

### Bearing Forces (SF=1.4)

<table>
<thead>
<tr>
<th>Case</th>
<th>Case</th>
<th>Trans.</th>
<th>Long.</th>
<th>Vert.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear Key Engaged</td>
<td>C</td>
<td>0</td>
<td>310</td>
<td>81104</td>
</tr>
<tr>
<td>(Load Path A)</td>
<td>U</td>
<td>0</td>
<td>108</td>
<td>-13355</td>
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</table>

### Bearing Forces (SF=1.0)

<table>
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<th>Case</th>
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<th>Long.</th>
<th>Vert.</th>
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<td>Shear Key Failed</td>
<td>C</td>
<td>10799</td>
<td>4770</td>
<td>57932</td>
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<td>(Load Path B &amp; C – See Note)</td>
<td>U</td>
<td>25287</td>
<td>1628</td>
<td>-9539</td>
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<td></td>
<td>T</td>
<td>30496</td>
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<tr>
<td></td>
<td>L</td>
<td>1340</td>
<td>13232</td>
<td>19255</td>
</tr>
</tbody>
</table>

Note: The same seismic demands are conservatively assumed for Load Path C.

**Table 1, Bearing Loads**

As mentioned previously, the loading on the model is assigned at the CG of the bearing shaft, which transfers the force from the bearing upper housing to the bearing lower housing.

The load is modeled as pressure loading applied at relevant surfaces, with some simplifications.
ASSUMPTIONS

Assumptions are made in this analysis model, due to various constraints. The assumptions might be implied in the model description above, but are summarized as follows:

1. The load transfer mechanism within the bearing might be more complicated than the simplified single node loading. But the current loading scheme is considered to capture the behavior with sufficient accuracy.
2. The stiffness of the supporting OBG structure, and the bearing shaft and lower housing, will affect the stress distribution of the upper housing. But it is considered to have minor effect and therefore is not included in this analysis.

3. No shearing and bearing action is considered for the bolt model, only axial tension with the corresponding friction that holds the various components of the model together.

CONCLUSIONS

A series of finite element analyses were performed to determine the response of the bearing upper housing to seismic loads. Of particular interest are the stresses induced by peak uplift and peak transverse and longitudinal loads (with orthogonal loads occurring simultaneously). In all cases, the effective stresses in the housing are less than the yield strength of the material (not counting stresses concentrations related to simplified load application and boundary conditions – these superficial concentrated stresses are of no concern).
Model Scope

1.0 * Concurrent Seismic Forces
Max Uplift, Without Shear Key
Max Longitudinal Shear, Without Shear Key
Max Transverse Shear, Without Shear Key

1.4 * Concurrent Seismic Forces
Max Uplift, With Shear Key

Friction Coefficients:
OBG-Upper Housing = 0.50 (Class B Surface)
Upper Housing-Shaft = 0 (Lubricated Surface)
Rigid Links between anchor blocks (green) and OBG soffit plate (orange) (typ.)

Rigid Links between anchor blocks (green) and A354 BD anchor rods (red) (typ.)

Rigid Links between upper housing (pink) and A354 BD anchor rods (red) (typ.)

Rigid Links between upper housing (pink) and surface of rigid cylindrical shaft (blue)

Point load applied at centroid of rigid cylinder, which is rigidly connected to the rigid cylindrical shaft

Typical Loading and Connections
1.0 * Concurrent Seismic Forces

Max Uplift, Without Shear Key
9.5 MN Upwards
25.3 MN Transverse
1.6 MN Longitudinal

Bearing Upper Housing
Von Mises Stresses

Localized stress concentration at rigid shaft connections
Anchor Rods
Axial Stresses

1.0 x Concurrent Seismic Forces
Max Uplift, Without Shear Key
9.5 MN Upwards
25.3 MN Transverse
1.6 MN Longitudinal

Peak Stress = 642 MPa = 0.67Fpu
Bearing Upper Housing Von Mises Stresses

1.0 * Concurrent Seismic Forces
Max Long. Shear Without Shear Key
19.3 MN Downwards
1.3 MN Transverse
13.2 MN Longitudinal
1.0 * Concurrent Seismic Forces
Max Long. Shear Without Shear Key
19.3 MN  Downwards
1.3 MN  Transverse
13.2 MN  Longitudinal

Anchor Rods
Axial Stresses

Peak Stress = 637MPa = 0.66Fpu

SAS_E2_BrgUp_201-204_Brg_Upper_Bolt_MaxLongiShear_WithoutSK_ISOVIEW2_AXIAL_STRESS
Bearing Upper Housing
Von Mises Stresses

1.0 * Concurrent Seismic Forces
Max Trans. Shear Without Shear Key
16.4 MN  Downwards
30.5 MN  Transverse
8.2 MN  Longitudinal

Localized stress concentration at rigid shaft connections
1.0 * Concurrent Seismic Forces
Max Trans. Shear Without Shear Key
16.4 MN  Downwards
30.5 MN  Transverse
8.2 MN  Longitudinal

Peak Stress = 641 MPa = 0.66Fpu
Bearing Upper Housing
Von Mises Stresses

1.4 * Concurrent Seismic Forces
Max Uplift With Shear Key
13.4 MN Upwards
0.0 MN Transverse
0.1 MN Longitudinal

SAS_E2_BrgUp_201-204_Brg_Upper_MaxUplift_WithSK_ISO_PosY_EFFECTIVE_STRESS
1.4 * Concurrent Seismic Forces
Max Uplift With Shear Key
13.4 MN Upwards
0.0 MN Transverse
0.1 MN Longitudinal

Peak Stress = 638MPa = 0.66Fpu

SAS_E2_BrgUp_201-204_Brg_Upper_Bolt_MaxUplift_WithSK_ISOVIEW2 AXIAL_STRESS
Appendix C – Bearing Lower Housing

FEM
ANALYSIS OF BEARING BOTTOM HOUSING FOR SEISMIC LOADS

Self-Anchored Suspension Bridge

San Francisco Oakland Bay Bridge East Span Seismic Safety Project

Caltrans Project No. 04-0120F4

T.Y. Lin International / Moffatt & Nichol Joint Venture

July 13, 2013
INTRODUCTION

The bearing bottom housing surrounds the spherical bushing assembly and transfers bearing loads to the bearing hold down assembly, see Figure 1.

Figure 1, Bearing assembly showing the bearing bottom housing.

This report summarizes a series of analyses demonstrating the response of the bearing bottom housing to seismic loads.

LOADS

Bearing forces were extracted from a seismic (time history) analysis of the self-anchored suspension bridge including the bearings and shear keys. The total longitudinal, transverse, and vertical loads transferred from the westbound and eastbound box girders to Pier E2 were extracted from the analysis and distributed to the bearings and shear keys in accordance with the plans. The bearing loads are shown in Table 1.

Normal functioning of the bearing corresponds to the case “Shear Key Engaged”. The bearing is only required to carry vertical loads. These are either downwards—case C—or upwards—case U. Upwards loads are of greatest concern and are addressed in this report. A “safety factor” of 1.4 is applied to the calculated loads from the seismic analysis.

The bearing is also intended to function as a secondary mechanism to resist longitudinal and transverse loads should the shear keys fail. The three cases of greatest interest are those corresponding to the peak uplift on the bearing (case U), the peak transverse load (case T), and the
peak longitudinal load (case L). In each case the orthogonal loads occurring simultaneously with the peak loads are also tabulated (and analyzed). These loads are applied with a “safety factor” of 1.0, since they are based on the conservative assumption that the shear key has failed.

<table>
<thead>
<tr>
<th>Case</th>
<th>Case</th>
<th>Trans.</th>
<th>Long.</th>
<th>Vert.</th>
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</thead>
<tbody>
<tr>
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<td>81104</td>
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<tr>
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<td>U</td>
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<td>108</td>
<td>-13355</td>
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<th>Long.</th>
<th>Vert.</th>
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<tr>
<td></td>
<td>T</td>
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</tr>
<tr>
<td></td>
<td>L</td>
<td>1340</td>
<td>13232</td>
<td>19255</td>
</tr>
</tbody>
</table>

Note: The same seismic demands are conservatively assumed for Load Path C.

Table 1, Bearing Loads

MODEL

Finite Element Model

The behavior of the bearing bottom housing was evaluated using the finite element model shown in Figure 2. This model was created using ADINA.

![ADINA model of bottom bearing housing](image)

Figure 2, ADINA model of bottom bearing housing

The body of the bottom bearing housing is colored green in Figure 2. The spherical bushing assembly is colored red. The interface between the housing and the bushing was modeled with a contact surface able to transfer compression only.
Loads

For simplicity, longitudinal and vertical loads were distributed over the vertical faces of the spherical bushing assembly, as shown in Figure 3.

Figure 3, Application of vertical and longitudinal loads

Transverse loads are transferred to the bearing bottom housing through contact with the bearing upper housing on the side faces of both housings. This contact is complex. For simplicity, transverse loads were applied to the bearing bottom housing on the bottom half of the perimeter of the opening in the housing, as shown in Figure 4.

Figure 4, Application of transverse loads

Boundary Conditions

The bearing bottom housing is restrained through contact with the bearing hold down assembly. In lieu of modeling this contact, the restraint was modeled by fixed boundaries applied to the
edges of the bearing bottom housing. The restrained edges were chosen to reflect the direction of
the applied loads. The restrained boundaries used to resist uplift on the housing are shown in Fig-
ure 5.

![Figure 5, Boundary conditions used to analyze uplift]

**RESULTS**

**Maximum Uplift (Safety Factor = 1.4)**

Assuming the shear key is functional, the loads on the bearing bottom housing are vertical. For
the critical case of uplift on the bearing, the computed effective (von Mises) stresses in the hous-
ing are shown in Figure 6.

![Figure 6, Effective stresses for maximum uplift (safety factor = 1.4)]

The peak stresses in the body of the housing are about 175 MPa, which is well below the yield
strength of the material of 550 MPa. Stresses on the restrained edges are also high. These overes-
timate the actual stresses because the contact of the housing with the hold down assembly will occur over some area rather than on an edge.

**Maximum Uplift (Safety Factor = 1.0)**

Assuming that the shear keys have failed, the bearings will resist longitudinal and transverse loads in addition to vertical loads. These loads are considered with a “safety factor” of 1.0. For the case of maximum uplift, the effective stresses are shown in Figure 7.

![Figure 7, Effective stresses for maximum uplift (safety factor = 1.0)](image)

There are high stresses around the bottom perimeter of the opening in the housing (where the spherical bushing assembly fits into the housing). This is due to the application of the transverse loads to the housing along this line. The stresses along this line overestimate the actual stresses in the housing because transverse loads will be applied over some contact area with the bearing top housing.

Aside from the aforementioned stress concentrations and those occurring along the restrained edges, the peak stresses in the housing are about 280 MPa.

**Maximum Transverse Load (Safety Factor = 1.0)**

Also assuming that the shear keys have failed, the effective stresses for the case of maximum transverse load are shown in Figure 8. Aside from stresses concentrations related to the (simplified) application of the loads and the boundary conditions, the peak stress in the housing is about 200 MPa.

**Maximum Longitudinal Load (Safety Factor = 1.0)**

Also assuming that the shear keys have failed, the effective stresses for the case of maximum longitudinal load are shown in Figure 9. Aside from stresses concentrations related to the (simplified) application of the loads and the boundary conditions, the peak stress in the housing is about 200 MPa.
CONCLUSIONS

A series of finite element analyses were performed to determine the response of the bearing bottom housing to seismic loads. Of particular interest are the stresses induced by peak uplift and peak transverse and longitudinal loads (with orthogonal loads occurring simultaneously). In all cases, the effective stresses in the housing are less than the yield strength of the material (not counting stresses concentrations related to simplified load application and boundary conditions – these superficial concentrated stresses are of no concern).
Appendix D – Bearing Hold Down
Assembly FEM
ANALYSIS OF BEARING LOWER HOUSING HOLD DOWN ASSEMBLY FOR SEISMIC LOADS

Self-Anchored Suspension Bridge
San Francisco Oakland Bay Bridge East Span Seismic Safety Project
Caltrans Project No. 04-0120F4

T.Y. Lin International / Moffatt & Nichol Joint Venture
July 15, 2013
INTRODUCTION

This study investigates the scenario of using only the permanent bearings to resist the seismic safety evaluation earthquake (SEE) load (without shear keys engaged – Load Path B and C).

MODEL

The study is conducted with an analysis model developed in Adina. As shown in the figure below, the model includes the bearing hold down assembly and supporting concrete frame. Both are modeled as solid elements. A total of 24-A354BD of 3-inch diameter anchor bolts are modeled as truss elements, with both ends fixed to the concrete and the hold down assembly. The anchor bolts are assigned with initial tension strain that simulates installed pre-tension and are modeled with an initial tension equivalent to 0.7fpu per the plans.

The hold down assembly includes three pieces: one base plate and two top pieces which are held down by the anchor bolts. The two top pieces have a split interface at the transverse CL of the pier. The hold down assembly is modeled based on the as-built condition, which includes larger chamfer in each individual anchor bolt hole.

To ensure analysis efficiency and accuracy, only a portion of the concrete pier is modeled. The bottom of the concrete model is fixed.

The resistance at interface of all model components is only static friction based on the contact pressure. Bolt shear capacity is not considered across the interface and is conservative. The contact surface between the faces of the hold down assembly pieces uses a coefficient of 0.5 which corresponds to a Class B surface. The contact surface between the hold down assembly and the concrete pier uses a coefficient of friction of 0.67 for the as-built condition.
LOADS

Bearing forces were extracted from a seismic (time history) analysis of the self-anchored suspension bridge including the bearings and shear keys. The total longitudinal, transverse, and vertical loads transferred from the westbound and eastbound box girders to Pier E2 were extracted from the analysis and distributed to the bearings and shear keys in accordance with the plans. The bearing loads are shown in Table 1.

Normal functioning of the bearing corresponds to the case “Shear Key Engaged”. The bearing is only required to carry vertical loads. These are either downwards—case C—or upwards—case U. Upwards loads are of greatest concern and are addressed in this report. A “safety factor” of 1.4 is applied to the calculated loads from the seismic analysis.

The bearing is also intended to function as a secondary mechanism to resist longitudinal and transverse loads should the shear keys fail. The three cases of greatest interest are those corresponding to the peak uplift on the bearing (case U), the peak transverse load (case T), and the peak longitudinal load (case L). In each case the orthogonal loads occurring simultaneously with the peak loads are also tabulated (and analyzed). These loads are applied with a “safety factor” of 1.0, since they are based on the conservative assumption that the shear key has failed.

<table>
<thead>
<tr>
<th>Case</th>
<th>Case</th>
<th>Trans.</th>
<th>Long.</th>
<th>Vert.</th>
</tr>
</thead>
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<tr>
<td>Shear Key Engaged</td>
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<tr>
<td>(Load Path A)</td>
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<td>310</td>
<td>81104</td>
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<tr>
<td></td>
<td>U</td>
<td>0</td>
<td>108</td>
<td>-13355</td>
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<tr>
<th>Case</th>
<th>Case</th>
<th>Trans.</th>
<th>Long.</th>
<th>Vert.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear Key Failed</td>
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<td></td>
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<tr>
<td>(Load Path B – See Note)</td>
<td>U</td>
<td>25287</td>
<td>1628</td>
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<td></td>
<td>T</td>
<td>30496</td>
<td>8186</td>
<td>16441</td>
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<td></td>
<td>L</td>
<td>1340</td>
<td>13232</td>
<td>19255</td>
</tr>
</tbody>
</table>

Note: The same seismic demands are conservatively assumed for Load Path C.

Table 1, Bearing Loads

The load is modeled as pressure loading applied at relevant surfaces, with some simplifications.
CONCLUSIONS

A series of finite element analyses were performed to determine the response of the bearing lower housing hold down assembly to seismic loads. Of particular interest are the stresses induced by peak uplift and peak transverse and longitudinal loads (with orthogonal loads occurring simultaneously). The analysis results are presented graphically for the four most critical load cases in Appendix A. The following can be concluded:

- **Load Path A:**
  - Case U: The effective stresses are less than yield.

- **Load Path B:**
  - Case L: The effective stresses are less than yield.
  - Case T: Localized yielding is expected at the edges where contact between the lower housing and the hold down assembly occurs. Note that the magnitude of the effective stresses are magnified by the simplified load application and boundary conditions.
  - Case U: Localized yielding may be expected at the corners where contact between the lower housing and the hold down assembly occurs. Note that the magnitude of the effective stresses are magnified by the simplified load application and boundary conditions.

For Load Path B (Case T and Case U), minor damage to the bearing lower housing hold down assembly is expected under the extreme event of SEE if all the shear keys failed. However, it is important to note that for Load Path C, the Transverse Shear at the Pier E2 Bent is shared among the four bearings (B1, B2, B3 and B4) and Shear Keys (S3 and S4) thereby reducing the demand by about a factor of 4/6, thereby reducing the stresses close to yield.
Model Scope

- 1.0 * Concurrent Seismic Forces
  - Max Uplift, Without Shear Key
  - Max Longitudinal Shear, Without Shear Key
  - Max Transverse Shear, Without Shear Key
- 1.4 * Concurrent Seismic Forces
  - Max Uplift, With Shear Key

- A354 BD Bolts
  - Connected to hold down at bolt hole locations using rigid links

- Contact surface between bottom plate and concrete

- Three distinct bodies for hold down assembly
- Contact surfaces at all interfaces

Pressure loads applied to interior faces of bearing hold down to simulate seismic loads transferred from lower housing. Simplified linear and uniform distribution used.

Friction Coefficients:
- Steel-Steel = 0.50
- Steel-Concrete = 0.67
ACINA: AUL version 8 & 2, 5 July 2013. Licensed from ADINA R&D, Inc.

SAS_E2_B4_111-114_Brg_HoldDown_MaxUplift_WithoutSK_ISOVIEW2_EFFECTIVE_STRESS_UnitMN.mrez

**Bearing Hold Down**

**Von Mises Stresses**

1.0 * Concurrent Seismic Forces
Max Uplift, Without Shear Key
9.5 MN Upwards
25.3 MN Transverse
1.6 MN Longitudinal

07/15/13

SAS_E2_B4_111-114_Brg_HoldDown_MaxUplift_WithoutSK_ISOVIEW2_EFFECTIVE_STRESS
Anchor Rods
Axial Stresses

1.0 * Concurrent Seismic Forces
Max Uplift, Without Shear Key
9.5 MN  Upwards
25.3 MN  Transverse
1.6 MN  Longitudinal

Peak Stress = 686MPa = 0.71Fpu

07/15/13
SAS_E2_B4_111-114_Brg_Bolt_MaxUplift_WithoutSK_ISOVIEW2_AXIAL_STRESS
1.0 * Concurrent Seismic Forces
Max Long. Shear Without Shear Key
19.3 MN  Downwards
1.3 MN  Transverse
13.2 MN  Longitudinal
Anchor Rods
Axial Stresses

1.0 * Concurrent Seismic Forces
Max Long. Shear Without Shear Key
19.3 MN  Downwards
1.3 MN  Transverse
13.2 MN  Longitudinal

Peak Stress = 678MPa = 0.70Fpu
**Bearing Hold Down**
**Von Mises Stresses**

**1.0 * Concurrent Seismic Forces**

- Max Trans. Shear Without Shear Key
  - 16.4 MN  Downwards
  - 30.5 MN  Transverse
  - 8.2 MN  Longitudinal

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**ADINA**

**SAS_E2_B4_111-114_Brg_HoldDown_MaxTransShear_WithoutSK_ISOVIEW2_EFFECTIVE_STRESS**

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**07/15/13**

**E2 Bearings - Hold Down Assembly Package_2013.07.15.pdf**
1.0 \times \text{Concurrent Seismic Forces}

- Max Trans. Shear Without Shear Key
  - 16.4 MN Downwards
  - 30.5 MN Transverse
  - 8.2 MN Longitudinal

Peak Stress = 688\,\text{MPa} = 0.71\,\text{Fpu}
1.4 * Concurrent Seismic Forces
Max Uplift With Shear Key
13.4 MN Upwards
0.0 MN Transverse
0.1 MN Longitudinal

07/15/13
SAS_E2_B4_111-114_Brg_HoldDown_MaxUplift_WithSK_ISOVIEW2_EFFECTIVE_STRESS
1.4 * Concurrent Seismic Forces
Max Uplift With Shear Key
13.4 MN Upwards
0.0 MN Transverse
0.1 MN Longitudinal

Peak Stress = 681 MPa = 0.71 Fpu
Appendix E – Pier E2 Push-Over Analysis
The superstructure supports at Pier E2 were developed with four (4) shear keys resisting the horizontal forces and four (4) bearings carrying the vertical loads. This design is based on the 1998 recommendation of the Seismic Safety Peer Review Panel (SSPRP) to have horizontal load carrying members separate and independent from the vertical load carrying members.

The shear keys were designed for the larger of:

- 1.4 times the Safety Evaluation Earthquake (from Time History Analysis)
- 1.15 times pushover strength of Pier E2 using maximum feasible material over-strength properties ($f'_{ce} = 1.7f'c$ for concrete and $f_{ye} = 1.3fy$ for rebar)

The 100% design considered prestressing the shear key stub down to the crossbeam and utilized shear friction to resist design horizontal force. The large prestressing force is required to provide adequate friction force as well as preventing any uplift, and this necessitated the use of large diameter, high-strength anchor rods.

<table>
<thead>
<tr>
<th>Seismic Demand</th>
<th>Design Shear (Max of 1.4 SEE or 1.15 Pushover)</th>
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</thead>
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<tr>
<td>Total Shear at Bent E2</td>
<td>Time History (Max of 6 SEE)</td>
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<tr>
<td>Longitudinal Shear</td>
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<tr>
<td>Transverse Shear</td>
<td>120 MN</td>
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</table>
Pier E2: Transverse Push-Over (Base Shear)

The graph shows the relationship between shear force in kn and drift in m. The shear force is plotted on the Y-axis, while the drift is plotted on the X-axis. Two curves are shown: one for E2 - North Base Shear and another for E2 - South Base Shear. The graph indicates that as the drift increases, the shear force also increases, reaching a peak and then stabilizing at higher drift values.