March 15, 2019

Stephen Wolf, P.E.
Principal
Metropolitan Transportation Commission
Bay Area Metro Center
375 Beale Street, Suite 800
San Francisco, CA 94105

RE: Transbay Transit Center
Review of Temporary Shoring Systems at Fremont Street and First Street

Dear Stephen:

This Peer Review Panel (PRP) was assembled by MTC at the request of the mayors of San Francisco and Oakland to review the activities undertaken in response to the fractured girders at the Transbay Transit Center (TTC). Our review was initially divided into the following five phases:

1. Capacity of the temporary shoring systems.
2. Sampling and testing plan for material from the fractured steel girders.
3. Cause of failure.
4. Impact of fractures on adjacent elements.
5. Repair of Fremont Street girders.

The results of the initial review may lead the panel to recommend other related investigations and analyses, which the panel may also subsequently review.

The purpose of this memo is to document the completion of our review of Phase 1, capacity of the temporary shoring systems. Our review included the temporary shoring systems both at Fremont Street and at First Street, installed to provide an alternative load path from the four TPG3 girders. In both cases, we did not review the initial shoring systems installed on an emergency basis that involved the use of very large hydraulic jacks placed at streel level provided by Bigge Crane and Rigging. Our review covered the subsequent more permanent, albeit still temporary, shoring systems that employed the use of hydraulic rams at street level provided by Sheedy Drayage Company.

Our review of the Fremont and First Street shoring systems was to ensure TJPA's project team performed proper due diligence in developing the design. We looked at the basis of design, structural concept and layout, overall stability, selected critical details, and selected calculations. Our scope did not include an in-depth review of all design details

and calculations nor a check for code compliance as this was done by other parties engaged by TJPA.

The process and results of our review are summarized separately below for the Fremont Street shoring and the First Street shoring.

Fremont Street Shoring

The review process included numerous online meetings between Thornton Tomasetti and the PRP. The major documents reviewed by the PRP throughout this process are as follows:

- Reports dated October 8 and October 10, 2018 by Thornton Tomasetti, titled: *Salesforce Transit Center – Fremont Street Shoring – Structural Calculations.*
- Memo dated October 13, 2018 from Steven Brokken of AECOM to Mark O'Dell of TJPA, with the subject: *Peer Review of Thornton Tomasetti Fremont Street Shoring at the Salesforce Transit Center.*
- Memo dated October 22, 2018 from Bruce Gibbons of Thornton Tomasetti to Mark O'Dell of TJPA, with the subject: *Shoring Design Peer Review Comments.*
- Drawings of the shoring system by Thornton Tomasetti, in the files: "20181022 TempShoringSet_TT.pdf," and "20181022 TempShoringSet_r1.pdf"
- Drawings and calculations by Thornton Tomasetti, in the file: "20181025 Stress Check in TPG3 @ GLE.6 with Composite Section Modulus.pdf"
- Memo dated October 30, 2019 from John Abruzzo to Dennis Turchon titled: *TPG-3 Grid Line 26 Bus Deck Shoring - Brace Calculation.*
- Drawings and calculations by Thornton Tomasetti, in the file: "20181205 Bending and Shear Demands in Fremont Shoring Due to Seismic Rocking.pdf"
- Drawings and calculations by Thornton Tomasetti, in the file" TPG3 Demands with reduced Jacking Forces 10-24-18.pdf"
- Drawings of the shoring system by Thornton Tomasetti, in the file: "TempShoringAtFremontStSet_TT20190108_wStamp.pdf"
    - Sheets: S1-8105; S1-8120 to 8123; S1-8130 to 8138.

Thornton Tomasetti addressed questions and comments from the PRP throughout this process. The PRP concurs with the design of the shoring system at Fremont Street. The basis of our concurrence is the final set of design drawings, which is the last item in the list above ("TempShoringAtFremontStSet_TT20190108_wStamp.pdf"), combined with the installation of additional lateral bracing for the W36x529 spreader beams at the bus deck level. This additional lateral bracing is not shown on the final set of design drawings, but has been installed.

First Street Shoring

The review process included numerous online meetings between Thornton Tomasetti and the PRP. The major documents reviewed by the PRP throughout this process are as follows:

- Report dated November 9, 2018 by Thornton Tomasetti, titled: *Salesforce Transit Center – First Street Shoring – Structural Calculations*
- Memo dated December 3, 2018 from Steven Brokken of AECOM to Mark O'Dell of TJPA, with the subject: *Review of Salesforce Transit Center First Street Shoring.*
- Calculations dated December 20, 2018 by Thornton Tomasetti, titled: *Hanger Compression Check.*
- Drawings of the shoring system by Thornton Tomasetti, in the file: "TempShoringAtFirstStreetSet_TT20181112_wStamp.pdf"
- Drawings of the shoring system by Thornton Tomasetti, in the file: "TempShoringAtFirstStreetSet_TT20181113_wStamp.pdf"
- Drawings of the shoring system by Thornton Tomasetti, in the file: "TempShoringAtFirstStreetSet_TT20190108_wStamp.pdf"
    - Sheets: S1-8205; S1-8220 to 8222; S1-8230 to 8231; S1-8234.

Thornton Tomasetti addressed questions and comments from the PRP throughout this process. The PRP concurs with the design of the shoring system at First Street. The basis of our concurrence is the final set of design drawings, which is the last item in the list above ("TempShoringAtFirstStreetSet_TT20190108_wStamp.pdf").

While the PRP has reviewed and concurs with the design of the shoring systems at Fremont Street and at First Street, the responsibility for the design remains with the engineer of record, and the in-depth engineering design check and regulatory review were done by others.

Sincerely,

Michael D. Engelhardt, P.E., Ph.D.
Chair, Peer Review Panel

c. Members of PRP:
John Fisher
Brian Kozy
Thomas Sabol
Robert Shaw

March 9, 2019

Stephen Wolf, P.E.
Principal
Metropolitan Transportation Commission
Bay Area Metro Center
375 Beale Street, Suite 800
San Francisco, CA 94105

RE: Transbay Transit Center
Review of TJPA Sampling and Testing Plan for Material from Fremont Street Girders

Dear Stephen:

This Peer Review Panel was assembled by MTC at the request of the mayors of San Francisco and Oakland to review the activities undertaken in response to the fractured girders at the Transbay Transit Center (TTC). Our review was initially divided into the following five phases:

1. Capacity of the temporary shoring system.
2. Sampling and testing plan for material from the fractured steel girders.
3. Cause of failure.
4. Impact of fractures on adjacent elements.
5. Repair of Fremont Street girders.

The results of the initial review may lead the panel to recommend other related investigations and analyses, which the panel may also subsequently review.

The purpose of this memo is to document the completion of our review of Phase 2, the TJPA plan for sampling and testing material from the fractured Fremont Street girders. The material sampling and testing was done to support analysis of the cause of the fractures and development of a repair plan. During the development of the plan, members of the PRP had a number of meetings with the TJPA project team, which includes the testing laboratory, engineer of record, contractor, and associated subcontractors, to review and discuss the plan. These meetings took place by conference call, as well as through in-person meetings at the TTC in San Francisco and at LPI, Inc. in New York. Our review started on October 15, 2018 with a meeting with the TJPA in San Francisco and site visit at the Transit Center, and was essentially completed with a visit of panel members to LPI, Inc. in New York on November 8, 2018.

Questions, concerns and recommendations from the PRP throughout this process were addressed by TJPA and reflected in the final material sampling and testing plan. That document, which forms the basis of our concurrence, is titled: "Transbay Transit Center Project – Girder Fracture Specimen Removal & Testing Protocol," dated 11.02.2018 Rev 4.

Our concurrence with the TJPA plan for sampling and testing material from the Fremont Street girders does not preclude future recommendations from the PRP for possible additional material sampling and testing, should we see the need for this as the investigation proceeds.

While the PRP has reviewed and concurs with the material sampling and testing plan, the responsibility for all aspects of the investigation of the fractured girders and resulting actions remains with the engineer of record.

Sincerely,

Michael D. Engelhardt, P.E., Ph.D.
Chair, Peer Review Panel

c. Members of PRP:
John Fisher
Brian Kozy
Thomas Sabol
Robert Shaw

January 6, 2020

Stephen Wolf, P.E.
Principal
Metropolitan Transportation Commission
Bay Area Metro Center
375 Beale Street, Suite 800
San Francisco, CA 94105

RE: Transbay Transit Center
Review of Cause of Failure

Dear Stephen:

This Peer Review Panel (PRP) was assembled by the Metropolitan Transportation Commission at the request of the mayors of San Francisco and Oakland to review the activities undertaken in response to the fractured girders at the Transbay Transit Center (TTC). Our review was initially divided into the following five phases:

1. Capacity of the temporary shoring systems.
2. Sampling and testing plan for material from the fractured steel girders.
3. Cause of failure.
4. Impact of fractures on adjacent elements.
5. Repair of Fremont Street girders.

As a result of undertaking the reviews noted above, two additional phases were added to the scope of our review:

6. Search for other areas susceptible to brittle fracture.
7. Review of TJPA's fatigue assessment plan.

This letter documents the completion of our review of Phase 3, cause of failure. To address key issues related to Phase 3, this letter is organized into the following sections:

- Purpose and scope of PRP review
- Basis of review
- Terminology
- PRP findings
- Additional issues related to the review

<u>Purpose and Scope of PRP Review</u>
The PRP review of the cause of failure pertains to ascertaining the cause of the fractures that occurred in the two tapered plate girders spanning over Fremont Street (designated in the design drawings as TPG3 girders). The purpose of the PRP review was to determine if the cause of these fractures is sufficiently well understood to allow a high degree of

confidence that the repairs undertaken for the Fremont Street girders are effective and safe. An additional purpose of our review was to determine if the cause of these fractures is sufficiently well understood to allow an effective review of other areas of the TTC structural framing that may be susceptible to brittle fracture.

The PRP did not undertake an independent analysis of the cause of failure or draw our own conclusions. Rather, the PRP reviewed work done by TJPA and its project team and consultants in establishing the cause of failure. The scope of the PRP review did not consider culpability of various parties in the fractures of the TPG3 girders. The PRP did not review whether the structural framing in place at the time of the fractures satisfied all requirements of the contract documents, design intent, or the standard of care expected in the design and construction of a major structure of the type found in the TTC. The PRP review also did not include application and interpretation of the governing standards and specifications in the execution of the design, fabrication, and construction. Rather, the PRP review was undertaken with a focus on the technical factors contributing to the fractures and a focus on structural safety.

As noted above, developing an adequate understanding of the cause of failure was important in determining that the repairs of the Fremont Street girders were effective and safe, and in properly informing the search for other areas in the TTC that may be susceptible to brittle fracture. The PRP conducted a review of the repairs of the Fremont Street girders as part of Phase 5 of our scope of work, and conducted a review of the search for other areas susceptible to brittle fracture as part of Phase 6 of our scope of work. The PRP reviews for Phases 5 and 6 are documented in separate letters from the PRP to the Metropolitan Transportation Commission, and will not be discussed further herein.

Basis of Review

In reviewing the cause of failure, the PRP interacted closely with TJPA and its project team and consultants starting in October of 2018 when the PRP was first established. The lead for TJPA in determining the cause of failure was LPI, Inc. (hereinafter referred to as "LPI"). Over approximately the last year, the PRP met with LPI numerous times for in-person meetings in San Francisco, Philadelphia, and New York and for on-line meetings and conference calls. The PRP reviewed several draft reports on the cause of failure prepared by LPI and provided comments and questions to LPI.

The result of the PRP review of the cause of failure, as documented in this letter, is based on the following final report issued by LPI, henceforth referred to as the "LPI Report":

- "Root Cause and Fitness-for-Service Assessments of TPG3 Fractured Girders Salesforce Transit Center San Francisco, CA" Document LA181690-R-002 Rev. 1, prepared by LPI, Inc., dated November 12, 2019.

Furthermore, this letter will refer only to the portions of the LPI Report that address the cause of the fractures. This letter will make no comment on other portions of the report

that are not pertinent to the cause of failure, such as LPI's fitness-for-service assessments of the TPG3 girders.

Terminology

In discussing the PRP review of the cause of failure, this letter will use terminology that differs from that used in the LPI Report. This difference in terminology pertains to openings cut in the bottom flanges of the TPG3 girders in the region where the fractures occurred.

In the mid-span region of each TPG3 girder, an opening was cut in the bottom flange to allow the hanger to pass through the bottom flange. The shape of this opening conforms to the shape of the hanger. This opening is referred to in this letter as the "primary slot."

In addition to the primary slot, two additional openings were cut into the bottom flange of each TPG3 girder. These two additional openings were cut in the region where the complete joint penetration groove weld in the bottom flange intersected the primary slot. These additional openings, one on either side of the primary slot, are referred to in this letter as "secondary slots." As documented in the LPI Report, the fractures in the TPG3 girders at Fremont Street initiated in the secondary slots. What the PRP refers to as "secondary slots" in this letter are referred to in the LPI Report as "weld access holes." The PRP is using the term "secondary slot" rather than "weld access hole" for reasons that will be discussed later in this letter in the section on Additional Issues Related to the Review.

PRP Findings

This section documents PRP findings on our review of the cause of failure presented in the LPI Report. Our findings are summarized as follows:

- The work conducted by LPI to establish the cause of failure was expansive and thorough. The work combined carefully conducted examinations of the physical evidence, extensive laboratory materials testing, the use of advanced finite element simulations, a strong knowledge of fracture mechanics, and previous experience in this type of investigation.

- The LPI Report presents a basic failure hypothesis for fracture of the Fremont Street girders and then provides data and analysis to support the hypothesis. Based on the PRP's interpretation of the LPI Report, the basic failure hypothesis is summarized as follows:

    - Thermal cutting of the secondary slots in the girder bottom flange produced microcracks in the radii of the reentrant corners of the secondary slots at mid-thickness of the bottom flange plate. The depth of the microcracks was on the order of several hundredths of an inch.
    - Some of the microcracks later became larger "pop-in" cracks at the mid-thickness of the girder's bottom flange plate, with a depth on the order of 3/8-inch. These pop-in cracks likely occurred due to tensile stresses generated by

weld area shrinkage from production of the complete joint penetration groove weld in the bottom flange.
- Sometime after the girders were erected, brittle fracture of the bottom flange occurred, initiating at the pop-in crack in the radius of the secondary slot at mid-thickness of the bottom flange plate and extending to the outer edge of the flange.
- The girder fractures were facilitated by the significantly low fracture toughness of the steel near mid-thickness of the 4-inch-thick bottom flange.
- The stress in the bottom flange that initiated the brittle fracture was a combination of:
  - residual stresses from the welding of the complete joint penetration groove weld in the bottom flange,
  - stresses from loads on the TPG3 girders after erection, with
  - a stress concentration effect caused by the reentrant corner of the secondary slot.

The PRP concurs with the basic failure hypothesis, as described above.

- The LPI Report presents analysis, including the use of advanced finite element simulations, to support the basic failure hypothesis. There are a large number of inputs into this analysis, and although determined using reasonable engineering judgment, many of these inputs remain subject to significant uncertainty and assumptions. These include:
  - the range of approximate dates when the fractures occurred,
  - the sequence of construction and application of loads to the structure after TPG3 girder erection,
  - the loads on the structure at the time the fractures occurred,
  - the method of determining the load effects on the TPG3 girders at the time of fracture based on the estimated loads on the structure and sequence of construction,
  - the welding residual stresses,
  - the temperature of the steel at the time of the fractures,
  - the fracture toughness of the steel based on Charpy-V-notch testing, and
  - the sequence of the three half-flange-width fractures that occurred in the two TPG3 girders at Fremont Street.

- LPI, working in conjunction with other TJPA project team members and consultants, and with input from the PRP, went to considerable effort to evaluate and reduce the likely magnitude of the uncertainties based on available data, sensitivity studies, and engineering judgement. Despite these efforts, significant uncertainties in the analysis remain.

- Despite these uncertainties and a small number of incidental inconsistencies in the LPI Report, the PRP believes the analysis presented in the LPI Report, in general, supports the basic failure hypothesis. Further, the available data and the analysis presented in the LPI Report, even considering analysis uncertainties, does not point to

other possible failure hypotheses. Thus, the PRP believes that the cause of failure, as represented by the basic failure hypothesis described earlier, is adequately understood to appropriately inform the repair of the Fremont Street girders and the search for other locations in the TTC susceptible to brittle fracture.

Additional Issues Related to the Review

As noted earlier, the scope of the PRP review did not include assessing culpability of various parties involved in the design and construction of the TTC in the fractures of the Fremont Street girders. It also did not include application and interpretation of the governing standards and specifications in the execution of the design, fabrication, and construction. As such, the concurrence of the PRP with the basic failure hypothesis, as described earlier in this letter, should not be construed as our concurrence with statements in the LPI Report that may be interpreted to imply culpability. In this regard, we would like to call attention to use of the term "weld access hole" in the LPI Report. As noted earlier, the PRP has used the term "secondary slot" in this letter to describe this feature. The PRP understands that the use of the term "weld access hole" has been an issue of contention in the wake of the girder fractures. The PRP did not undertake a review to determine if the term "weld access hole" is appropriate for these openings in the girder flange, whether based on applications of the term "weld access hole" in national building standards such as the AISC *Specification for Structural Steel Buildings* (ANSI/AISC 360) and the AWS *Structural Welding Code-Steel* (AWS D1.1) or based on requirements of the contract documents. As such, the PRP neither endorses nor refutes the use of the term "weld access hole" in the LPI Report, and consequently has used the term "secondary slot" in this letter.

Sincerely,

Michael D. Engelhardt, P.E., Ph.D.
Chair, Peer Review Panel

c. Members of PRP:
John Fisher
Brian Kozy
Thomas Sabol
Robert Shaw
Bill Mohr (consultant to PRP)

June 5, 2019

Stephen Wolf, P.E.
Principal
Metropolitan Transportation Commission
Bay Area Metro Center
375 Beale Street, Suite 800
San Francisco, CA 94105

RE: Transbay Transit Center
Review of study on the impact of fractures on adjacent elements

Dear Stephen:

This Peer Review Panel (PRP) was assembled by MTC at the request of the mayors of San Francisco and Oakland to review the activities undertaken in response to the fractured girders at the Transbay Transit Center (TTC). Our review is currently divided into the following six phases, the sixth being added after the mechanics of the fracture became evident in December:

1. Capacity of the temporary shoring systems.
2. Sampling and testing plan for material from the fractured steel girders.
3. Cause of failure.
4. Impact of fractures on adjacent elements.
5. Repair of Fremont Street girders.
6. Search for other areas susceptible to brittle fracture.

The results of the review may lead the panel to recommend other related investigations and analyses, which the panel may also subsequently review.

The purpose of this memo is to document the completion of our review of Phase 4, impact of fractures on adjacent elements. In this phase, TJPA and their consultants conducted a study to determine if the occurrence of the bottom flange fractures of the Fremont Street girders may have caused damage to adjacent structural elements.

The study undertaken by TJPA and their consultants was thorough, and included analysis of: the additional vertical deflection of the girders due to the flange fractures; the impact of this additional deflection on adjacent members at the bus deck and roof levels; the redistribution of bending moments in the girders due to the flange fractures; and the impact of this redistribution on adjacent structural elements. The study also included visual examination of the fractured girders, including the connections between the girder ends and the adjacent columns and the connections of beams framing into the fractured girders. The visual inspections were supplemented by nondestructive testing of the bolts

at the girder end connections and nondestructive testing of the bottom flange complete joint penetration groove welds closest to the fractures. This study by TJPA and their consultants concluded that the occurrence of the fractures at the Fremont Street girders did not damage adjacent structural elements.

We have determined that the approach by TJPA and their consultants in this study is reasonable and appropriate, and their conclusions are supported by the documented observations, data collected, and analysis results. Our determination is based on the details and results of the study presented to the PRP in several in-person and on-line meetings between December of 2018 and May of 2019, as well as the following report:

> "Inspection of TPG3 Framing Connections; Salesforce Transit Center."
> Prepared by Thornton Tomasetti, Document No. S18099.00
> Draft dated April 30, 2019

While the PRP has reviewed the study on the impact of fractures on adjacent elements, the responsibility for safety of the structure of the Transbay Transit Center remains with the engineer of record.

Sincerely,

Michael D. Engelhardt, P.E., Ph.D.
Chair, Peer Review Panel

c. Members of PRP:
John Fisher
Brian Kozy
Thomas Sabol
Robert Shaw

March 15, 2019

Stephen Wolf, P.E.
Principal
Metropolitan Transportation Commission
Bay Area Metro Center
375 Beale Street, Suite 800
San Francisco, CA 94105

RE: Transbay Transit Center
Review of Designs for Repair of Fremont Street Girders and Retrofit of First Street Girders

Dear Stephen:

This Peer Review Panel (PRP) was assembled by MTC at the request of the mayors of San Francisco and Oakland to review the activities undertaken in response to the fractured girders at the Transbay Transit Center (TTC). Our review was initially divided into the following five phases:

1. Capacity of the temporary shoring systems.
2. Sampling and testing plan for material from the fractured steel girders.
3. Cause of failure.
4. Impact of fractures on adjacent elements.
5. Repair of Fremont Street girders.

The results of the initial review may lead the panel to recommend other related investigations and analyses, which the panel may also subsequently review.

The purpose of this memo is to document the completion of our review of Phase 5, repair of Fremont Street girders. The repair is meant to restore the structural capacity of the bottom flanges of the fractured tapered plate girders over Fremont Street (designated in the design drawings as TPG3), and consists of dressing requirements for the existing material and a new steel sandwich plate design bolted across the fractures.

This memo also documents the completion of our review for a related item, the design of the retrofit of First Street girders. Although the two TPG3 girders over First Street did not fracture and were subject to a different sequence of fabrication that substantially minimized that risk, the PRP concurs with TJPA's decision to further mitigate the risk and consequences of fracture by retrofitting the girders. The retrofit provides redundant capacity to the bottom flanges of the TPG3 girders over First Street. The design is similar to that at Fremont Street, with modifications accounting for the intact flange.

The review process included numerous online meetings as well as in-person meetings between Thornton Tomasetti and the PRP. The review extended over several months, starting with initial discussions of the design concepts and then continuing through evaluation of the detailed design.

Thornton Tomasetti addressed questions and comments from the PRP throughout this process. The PRP concurs with the design of the repair of the Fremont Street girders and the design of the retrofit of the First Street girders.

The basis of our concurrence for Fremont Street is:

- The final set of design drawings prepared by Thornton Tomasetti, dated January 28, 2019. The drawings are titled: "Fremont Street TPG3 Girders Repair Sections and Details," and are marked "Issued for Construction."
    - Sheets: S1-8401 to 8403.

The basis of our concurrence for First Street is the following documents:

- The final set of design drawings prepared by Thornton Tomasetti, dated February 22, 2019. The drawings are titled: "First Street TPG3 Girders Repairs and Details," and are marked "Issued for Construction."
    - Sheets: S1-8404 to 8406.
- Document: LA181690-PR-003 TTC TPG3 Hanger Blend Grinding Procedure - Rev 2A.
- Document: LA181690-PR-004 TTC TPG3 Hanger Needle Peening Procedure - Rev 1A.

While the PRP has reviewed and concurs with the design of the repair of the Fremont Street girders and the retrofit of the First Street girders, the responsibility for the design remains with the engineer of record.

Sincerely,

Michael D. Engelhardt, P.E., Ph.D.
Chair, Peer Review Panel

c. Members of PRP:
John Fisher
Brian Kozy
Thomas Sabol
Robert Shaw
Bill Mohr (consultant to PRP)

January 16, 2020

Stephen Wolf, P.E.
Principal
Metropolitan Transportation Commission
Bay Area Metro Center
375 Beale Street, Suite 800
San Francisco, CA 94105

RE: Transbay Transit Center
Search for other areas susceptible to brittle fracture

Dear Stephen:

This Peer Review Panel (PRP) was assembled by the Metropolitan Transportation Commission at the request of the mayors of San Francisco and Oakland to review the activities undertaken in response to the fractured girders at the Transbay Transit Center (TTC). Our review was initially divided into the following five phases:

1. Capacity of the temporary shoring systems.
2. Sampling and testing plan for material from the fractured steel girders.
3. Cause of failure.
4. Impact of fractures on adjacent elements.
5. Repair of Fremont Street girders.

As a result of undertaking the reviews noted above, two additional phases were added to the scope of our review:

6. Search for other areas susceptible to brittle fracture.
7. Review of Transbay Joint Powers Authority's (TJPA's) fatigue assessment plan.

This letter documents the completion of our review of Phase 6, Search for other areas susceptible to brittle fracture. To address key issues related to Phase 6, this letter is organized into the following sections:

- Scope of the Search
- Scope and Basis of PRP Review
- PRP findings

Scope of the Search

The cause of the brittle fracture of the tapered plate girders over Fremont Street (the fracture hypothesis) is summarized in the PRP's letter to MTC dated January 6, 2020, and was understood with enough certainty in December 2018 to lead TJPA to initiate a building-wide search for other locations in the steel structure that might also be

susceptible to brittle fracture (the Search). As in the other phases of the peer review, TJPA's project team was responsible for performing the investigation and drawing conclusions, and the PRP reviewed this work to evaluate whether the investigation was conducted with proper care and the conclusions were sound. TJPA's project team for the Search was led by the TTC's engineer of record, Thornton Tomasetti Inc. (TT), with analytical support provided by TJPA's failure analysis consultant, LPI, Inc. (LPI).

As a precursor to the Search, the PRP performed a preliminary scan of select areas of the steel structure to identify examples of the kinds of conditions the TJPA project team should be searching for and reviewing. The PRP was assisted during this preliminary scan by Ruby + Associates, Inc. (Ruby), a structural engineering firm in Southfield, Michigan with a focus on steel construction. Design drawings were supplied to the PRP by TJPA, and an initial presentation was made to the TJPA project team in December 2018 of design details to be considered for further evaluation. Subsequently, fabrication shop drawings and erection drawings were provided to the PRP, and a further scan of selected bays and members was conducted. The PRP identified several additional locations and details in the structure that warranted review by TJPA's project team, and a more detailed presentation was made by Ruby in late January 2019.

The PRP suggested the following members and details for identification and review by TT:

- Members:
  - Thick rolled wide-flange sections with flange thicknesses of 2 inches or greater.
  - Built-up sections that use plates with thicknesses of 2 inches or greater.
  - Column sections with varying web thicknesses transitioned by welding with thermal cut holes at the end of web groove welds.
  - Built-up sections with web-to-flange welds that transition from groove welds (with or without reinforcing fillets) to fillet welds only, at the transition location, where thermally cut holes may have been used at the transition.
  - Built-up sections with flange splices and/or web splices where cope holes may or may not have been provided at splice locations (situation depends upon splice and assembly sequence).
  - Other members of considerable complexity of assembly or welding, where the thickness is less than 2 inches (particularly box members and members associated with the perimeter HSS framing system).

- Details when present in the above members:
  - Typical use, size and detailing of weld access holes, as represented by the *AISC 360 Specification* and the *AISC 341 Seismic Provisions* (both 2010 and 2016).
  - Typical use, size and detailing of beam copes, as represented by the *AISC 360 Specification* and the *AISC 341 Seismic Provisions* (both 2010 and 2016).
  - Other similar holes or copes that may have been added for stress relief or to provide access accommodations for assembly of components or for welding.
  - Thermally cut connection components used in drag connections, with a thickness of 1-1/2 inches or greater.
  - Weld intersections of groove welds, in two directions and in three directions.

- Conditions of high constraint, hence high residual stresses.
- Welded joints with difficult access for welding.
- Re-entrant corners (e.g. trimming of beam flanges to width).
- Re-entrant corners and copes of connection material that is 2 inches thick or more.
- Tapering of flange sections to width.
- Web penetrations in rolled sections with web thicknesses exceeding 2 inches.

Scope and Basis of PRP Review

With the above input from the PRP, TT completed a search of the entire TTC steel structure for the conditions suggested above, as well as other conditions identified by TT.

The result of the PRP review of the Search, as documented in this letter, will refer to the following final report issued by TT:

- "Interim Report 7: Brittle Fracture Review Rev 1, prepared by Thornton Tomasetti, dated January 6, 2020.

This report, henceforth termed the TT Report, summarizes the process employed by TT and others in Appendix A of the report, as follows:

> "The investigation began with the task of identifying details which were more susceptible to failure by brittle fracture for one reason or another. We found 46 items for which we needed more information than that provided in the construction documents to resolve. We investigated each item and through a process of further inquiry of the contractors, review of photographs, design stresses, inspection records, and other documents we were able to alleviate concern. Some items required action beyond review of documents with verification by removal of finishes to expose the steel for visual observation, testing, further analysis, measurements, etc."

The TT Report itemizes these 46 items, identifies representative design drawings and shop drawings, and provides a description of the member and the issues to be addressed; the designated investigation category; and the results of the investigation, including the rationale for resolution. This was supported by separate files containing the representative shop drawings, and where appropriate, shop and field photographs, request for information (RFI) submittals and resolutions, photographs of specific joints that had been exposed for visual and tactile examination, and calculations of stresses at the joint or in the member.

Items 5 & 6, Column Web Transition Weld Details, required a more extensive sampling and physical review than other conditions, including removal of architectural finishes and nondestructive tests of joints considered at risk of brittle fracture. This nondestructive testing and the fitness for purpose evaluation that followed were performed by LPI and is summarized in the TT Report.

PRP Findings

This section documents PRP findings on our review of the search for other areas susceptible to brittle fracture, as presented in the TT Report. Our findings are summarized as follows:

- The work conducted by TT to search for and evaluate other areas of the TTC steel structure that could be susceptible to brittle fracture was thorough and extensive, as described in Appendix A of the TT Report.
- The TT Report summary table and supporting documentation was sufficient for the PRP to evaluate the search conducted and the evaluation made by TT.

The PRP review of the Search, performed concurrently with the TJPA project team's work of the Search, was done through in-person meetings in San Francisco and New York City, as well as numerous web meetings. The PRP was also represented during on-site examinations of several locations where fireproofing material was removed for visual and tactile evaluation.

The PRP believes the project team and consultants to the TJPA performed the proper due diligence in the building-wide search for other locations in the steel structure that might be susceptible to brittle fracture and in satisfactorily addressing issues arising from this search.

Sincerely,

Michael D. Engelhardt, P.E., Ph.D.
Chair, Peer Review Panel

c. Members of PRP:
John Fisher
Brian Kozy
Thomas Sabol
Robert Shaw
Bill Mohr (consultant to PRP)

November 11, 2019

Stephen Wolf, P.E.
Principal
Metropolitan Transportation Commission
Bay Area Metro Center
375 Beale Street, Suite 800
San Francisco, CA 94105

RE: Transbay Transit Center
Review of TJPA's Fatigue Assessment Plan

Dear Stephen:

This Peer Review Panel (PRP) was assembled by the Metropolitan Transportation Commission at the request of the mayors of San Francisco and Oakland to review the activities undertaken in response to the fractured girders at the Transbay Transit Center (TTC). Our review was initially divided into the following five phases:

1. Capacity of the temporary shoring systems.
2. Sampling and testing plan for material from the fractured steel girders.
3. Cause of failure.
4. Impact of fractures on adjacent elements.
5. Repair of Fremont Street girders.

As a result of undertaking the reviews noted above, two additional phases were added to the scope of our review:

6. Search for other areas susceptible to brittle fracture.
7. Review of TJPA's fatigue assessment plan.

The purpose of this memo is to document the completion of our review of Phase 7. The PRP identified fatigue as a potential concern since the TTC structure will be exposed to repeated bus loading throughout its service life, and there is the possibility that fatigue damage may accumulate over time and lead to fracture. It is the understanding of the PRP that fatigue was considered in the original design of the TTC. However, the detailed treatment of fatigue in the original design was not included in the documentation provided to the PRP. Consequently, the PRP requested a reassessment of the design of the TTC structural framing for fatigue.

In Phase 3, Cause of Failure (still underway), TJPA's consultants have shown fatigue was not a contributing factor in the girder fractures. As a result, TJPA, MTC and the PRP mutually agreed to limit the PRP's scope in Phase 7 to a review of the methodology that

will be used to determine if fatigue is a concern in the future performance of other parts of the TTC structural framing, and that TJPA's consultants would complete the analysis subsequently. It is not within the PRP's scope to review this subsequent implementation of the methodology or its results.

The methodology for evaluating fatigue was developed by TJPA consultants Thornton Tomasetti and LPI, Inc. The PRP review included reviewing draft reports outlining the fatigue methodology, and a series of online meetings with Thornton Tomasetti and LPI.

Thornton Tomasetti and LPI addressed questions and comments from the PRP throughout this process. The PRP concurs with the conservative methodology developed by Thornton Tomasetti and LPI for determining if fatigue is a concern in the future performance of the TTC structural framing. The basis of our concurrence is the following report:

- "Salesforce Transit Center – Interim Report 8 (Draft): Fatigue Review of Bus Deck," prepared by John Abruzzo, Thornton Tomasetti, dated October 11, 2019.

While the PRP has reviewed and concurs with the methodology to evaluate the fatigue performance of Transbay Transit Center structural framing, the responsibility for the design remains with the engineer of record.

Sincerely,

Michael D. Engelhardt, P.E., Ph.D.
Chair, Peer Review Panel

c. Members of PRP:
John Fisher
Brian Kozy
Thomas Sabol
Robert Shaw
Bill Mohr (consultant to PRP)