EFFECT OF FINGER EXPANSION JOINTS ON SEISMIC RESPONSE OF BRIDGES

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This paper presents the effect of steel finger-type expansion joints on the overall seismic response of a bridge. For this purpose, two nonlinear hysteretic models are developed for finger expansion joints. Complex interaction of longitudinal and transverse hysteretic behavior such as slip-out, collision, and failure of fingers is included in the models. The models are implemented to seismic response analysis of a three-span simply supported bridge. It is found from the analysis that the effect of expansion joints is significant in the plastic curvature of columns at their plastic hinge and the response displacement and residual displacement of decks and columns.

Key Words : seismic design, bridges, dynamic analysis, expansion joint, earthquake, pounding, damage

1. INTRODUCTION

It becomes important to take account of the effect of expansion joints into the seismic response analysis of long multi-span continuous bridges. However research on the effect of expansion joints on the seismic response of bridges is very limited and the past efforts have been concentrated on the enhancement of durability, cold resistance and noise-resistance of expansion joints. For example, Matsumoto, Yamaguchi et al. experimentally studied the mechanism of noise generation and noise control for modular expansion joints$^1$ while Abe et al. studied the variation and attenuation of applied load at expansion joints due to gap based on laboratory experiments$^2$.

However, because an expansion joint is a cheaper component than other structural components in bridges, it has been regarded as a minor structural component and thus only limited studies were conducted on the effect of expansion joints on the seismic response of bridges of expansion joints. Various types of damage were developed in past earthquakes such as the 1995 Kobe, Japan earthquake$^3$. For example, in the steel finger-type expansion joints, face-plates were detached from the slabs due to rupture of anchor bolts, fingers were bent and uplifted due to crash under extensive compression, fingers were locked together between the adjacent decks, and fingers slipped out and settled (refer to Photo 1). In rubber expansion joints, the expansion joints suffered extensive damage and the connections of expansion joints with the concrete slabs were damaged (refer to Photo 2). The damage of expansion joints occurred not only in Japan but also in the 1994 Northridge, USA earthquake and in the 1999 Chi Chi, Taiwan earthquake$^4,5$.

The damage of expansion joints not only affects the function of a bridge immediately after an earthquake but also results in a significant impact on the overall seismic response of a bridge. In recent years, there have been many studies about pounding between girders. For example, Shoji, Kawashima et al. studied the effectiveness of rubber shock absorbing devices for mitigating the pounding effect between adjacent decks based on a series of shake table experiments$^6$. Takeno and Izuno studied the usefulness of the collision velocity spectra for evaluating the pounding effect between adjacent decks$^7$, and Moriyama and Yoda studied the effect of pounding based on a two-dimensional shake table experiment$^8$. Furthermore, Matsumoto and Kawashima studied possible failure modes due to the progressive failure of main structural components for a three-span simply supported bridge$^9$. 
In the above studies, it is assumed that bridge decks directly collide\textsuperscript{10,11}, but in fact expansion joints restrain the relative movement of decks before collisions. The effect of expansion joints has not yet been fully considered in analysis.

After the 1995 Kobe, Japan earthquake, elastomeric bearings as well as lead rubber bearings and high damping rubber bearings are extensively used. Although it is expected that extensive damage of bearings which occurred during past major earthquakes is mitigated by the use of elastomeric bearings, it results in an increase of deck response displacement. Consequently, it is important to take into account the effect of expansion joints on the overall bridge response. Because it is anticipated that failure of expansion joints could affect the response of bridges, it is interesting to clarify the failure mechanism of expansion joints.

In this paper, the effect of steel finger-type expansion joints on the overall seismic response of bridges is studied by developing two nonlinear hysteretic models of expansion joints which can take the longitudinal and transversal interaction into account.

2. IDEALIZATION OF FINGER EXPANSION JOINTS

A steel finger-type expansion joint generally consists of n-set of fingers which are fixed at their base to the left deck and the other n-set of fingers which are fixed to the right deck as shown in Fig. 1. Relative displacement between the left and right decks is accommodated by the relative movement between the fingers fixed to the left deck and those fixed to the right deck. A finger fixed to the left deck at its base and a finger next to this finger fixed to the right deck is called as adjacent finger. Longitudinal gap between the tip of a finger and the base of the adjacent finger and the transverse gap between two adjacent gap $\Delta l_{EJ}$ and the transverse gap $\Delta w_{EJ}$, respectively.

Representing the length, width and height of a finger as $l_{EJ}$, $w_{EJ}$ and $h$, the effective finger length $l_{EJ,e}$ is defined as

$$l_{EJ,e} = l_{EJ} - \Delta l_{EJ}$$  \hspace{1cm} (1)

Representing the response displacement of the left and right decks in the longitudinal and transverse directions as $u_k$ and $v_k$ ($k = l$ and $r$), respectively, the longitudinal and transverse relative displacement between the two decks, $\Delta u$ and $\Delta v$, are defined as

$$\Delta u = u_r - u_l$$
$$\Delta v = v_r - v_l$$  \hspace{1cm} (2)

The longitudinal and transverse lateral forces which are developed in an expansion joint corresponding to $\Delta u$ and $\Delta v$ are designated here as $F_u$ and $F_v$. It is noted that fingers slip out from their contact position when $\Delta u$ becomes larger than the effective finger length $l_{EJ,e}$.

An important mechanical property of an expansion joint is its strong hysteretic behavior depending on the relative displacements $\Delta u$ and $\Delta v$. Furthermore, the hysteretic behavior in the longitudinal direction and that in the transverse direction are coupled. It should be noted here that in reality longitudinal and transverse displacements are coupled with rotation of decks about the vertical axis between the adjacent
(1) Hysteretic behavior of an expansion joint prior to failure

Consider a set of fingers which moves in the longitudinal direction. When the tips of fingers at one side and the bases of the fingers at the other side are not in contact under compression ($\Delta u > -\Delta l_{EJ}$) or they do not slip out from their contact position under tension ($\Delta u < l_{EJ,e}$), the transverse relative displacement $\Delta v$ is constrained within the transverse gap $\Delta w_{EJ}$ ($|\Delta v| < \Delta w_{EJ}$). However, once the transverse relative displacement $\Delta v$ reaches the transverse gap $\Delta w_{EJ}$ ($|\Delta v| \geq \Delta w_{EJ}$), a transverse force $F_v$ is induced, and if $F_v$ builds up to the transverse strength of the expansion joint $P_v$, the expansion joint fails.

On the other hand, once fingers at one side completely slip out from the fingers at the other side in the longitudinal direction ($\Delta u \geq l_{EJ,e}$) the expansion joint can freely displace in the transverse direction over $\Delta w_{EJ}$. However when $\Delta u$ decreases to reach $l_{EJ,e}$ with the transverse displacement $\Delta v$ being larger than $\Delta w_{EJ}$ ($|\Delta v| \geq \Delta w_{EJ}$), the adjacent fingers collide at their tips resulting in a contact (compression) force $F_u$, and the fingers at both sides cannot return to their original position. If the compression force $F_u$ reaches the longitudinal capacity $P_u$ of the expansion joint, the expansion joint fails in compression.

It may not be theoretically impossible for an expansion joint to slip into the original position if the expansion joint transversely displaces $n$ times $w_{EJ} + \Delta w_{EJ}$ under the condition of $\Delta u > l_{EJ,e}$. However, it is likely that the expansion joint suffers significant damage once the transverse relative displacement $\Delta v$ becomes excessively large. Consequently it is assumed here that the expansion joint cannot slip longitudinally into the original position once the expansion joint transversely displaces over $w_{EJ} + \Delta w_{EJ}$.

Similarly, a compression force $F_u$ is developed in an expansion joint if the tips of fingers at one side start to contact with the base of the fingers at the other side when the expansion joint is subjected to compression. If the compression force $F_u$ reaches the compression capacity of the expansion joint $P_{uc}$, the expansion joint fails in compression.

It is important how to evaluate the strengths $P_v$, $P_u$ and $P_{uc}$. Obviously, experimental verification is required for the evaluation of strengths of expansion joints, but sufficient and reliable data are hardly available at this moment. Therefore assuming that failure of an expansion joint occurs not at the connection with the slabs but in the fingers, $P_v$ is evaluated based on the full plastic flexure strength of fingers, and $P_u$ and $P_{uc}$ are evaluated based on the buckling strength of fingers as

$$P_v = n \frac{w_{EJ} \sigma_y}{4(3/4 l_{EJ})}$$

$$P_u = n \frac{\pi^2 EI}{4l_{EJ}^2}$$

$$P_{uc} = 2n \frac{\pi^2 EI}{4l_{EJ}^2}$$

in which, $w_{EJ}$ and $h$: width and height of a finger, $\sigma_y$: yield stress of the fingers and $EI$: flexural rigidity about the weak axis (transverse direction) of a finger. $P_v$ was evaluated by assuming that the adjacent fingers come in contact at three quarters of the
finger length \((3/4 l_{EJ})\).

Based on the above assumptions, the restoring force vs. relative displacement hysteresis of an expansion joint in the longitudinal and transverse directions may be written as

\[
F_u = \begin{cases} 
0 & -N_{EJ} < \Delta u < l_{EJ} \\
k_{EJu}(\Delta u + N_{EJ}) & -N_{EJB} < \Delta u < -N_{EJ} \\
\frac{N_{EJB}}{l_{EJ}} \Delta u - l_{EJ} & \text{once after } \Delta u > l_{EJ} \\
k_{EJ}(\Delta \nu - \Delta w_{EJ}) & \text{once after } \Delta u > l_{EJ} \\
0 & |\Delta \nu| < \Delta w_{EJ} \text{ and } \Delta u < l_{EJ} \\
0 & |\Delta \nu| > \Delta w_{EJ} \text{ and } \Delta u < l_{EJ} \\
\end{cases}
\]

\[
F_v = \begin{cases} 
0 & -N_{EJ} < \Delta \nu < l_{EJ} \\
k_{EJu}(\Delta u - N_{EJ}) & -N_{EJB} < \Delta u < -N_{EJ} \\
\frac{N_{EJB}}{l_{EJ}} \Delta u + l_{EJ} & \text{once after } \Delta u > l_{EJ} \\
k_{EJ}(\Delta \nu - \Delta w_{EJ}) & \text{once after } \Delta u > l_{EJ} \\
0 & |\Delta \nu| < \Delta w_{EJ} \text{ and } \Delta u > l_{EJ} \\
0 & |\Delta \nu| > \Delta w_{EJ} \text{ and } \Delta u > l_{EJ} \\
\end{cases}
\]

in which, \(\Delta u\) and \(\Delta \nu\), \(l_{EJ}\), \(l_{EJe}\), \(w_{EJ}\) and \(\Delta w_{EJ}\) are the parameters already defined, and \(\Delta l_{EJB}\): longitudinal relative displacement at the instance when a finger fails in compression, \(\Delta v_{EJB}\): longitudinal relative displacement at the instance when fingers fail in compression after fingers once slipped out and then start to contact, \(\Delta w_{EJB}\): transverse relative displacement at the instance when fingers fail due to contact with adjacent fingers, \(\Delta v_0\): transverse relative displacement at the instance when fingers start to contact with the fingers at the other side after they once longitudinally slipped-out, \(k_{EJu}\) and \(k_{EJ}\): the compressive and flexural stiffnesses of an expansion joint in the longitudinal and transverse directions, respectively, and \(k_{EJu0}\): the longitudinal compression stiffness of an expansion joint when fingers start to contact after they once slipped out.

It should be noted in Eqs. (6) and (7) that because \(F_u\) and \(F_v\) are coupled depending on \(\Delta u\) and \(\Delta \nu\), these have to be solved considering the interaction between \(F_u\) and \(F_v\).

**Fig. 2** shows the \(F_u\) vs. \(\Delta u\) hysteresis, and \(F_v\) vs. \(\Delta \nu\) hysteresis of an expansion joint. The hysteresis after an expansion joints fails, which will be described later, are also shown here.

The stiffnesses of an expansion joint, \(k_{EJu}\), \(k_{EJu0}\) and \(k_{EJ}\), are defined as

\[
k_{EJu} = 2n \frac{EA}{l_{EJ}} \\
k_{EJu0} = n \frac{EA}{l_{EJ}}
\]

where, \(EA\) and \(EI\) are an axial stiffness and flexural stiffness about the weak axis, respectively. It is assumed in the evaluation of \(k_{EJu}\) by Eq. (8) that adjacent fingers contact at \(3/4 l_{EJ}\) similar to the evaluation of \(P_v\) by Eq. (3).

(2) Hysteretic behavior of an expansion joint after failure

Among several possible failure modes which could be developed in a finger expansion joint, two extreme failure modes are considered here (refer to Fig. 2).

**a) Failure without lock of fingers**

If an expansion joint fails and completely looses its restoring force either in the longitudinal or transverse direction, it is likely that the expansion joint looses the restoring force in the other direction. If an expansion joint transfers only the friction force after its failure, the resultant restoring force vs. relative displacement hysteresis of an expansion joint may be expressed as

\[
F_u = \begin{cases} 
-P_{uc} + k_{EJuB}(\Delta u + \Delta l_{EJB}) & \Delta l_{EJB} + P_{uc}/k_{EJuB} \leq \Delta u < -\Delta l_{EJB} \\
-P_{uc} + k_{EJuB}(\Delta u - \Delta l_{EJB}) & \Delta l_{EJB} + P_{uc}/k_{EJuB} \leq \Delta u \leq \Delta l_{EJB} \\
0 & \Delta l_{EJB} + P_{uc}/k_{EJuB} \leq \Delta u < l_{EJ} \\
\pm F_b & |\Delta \nu| \geq \Delta w_{EJB} \\
\end{cases}
\]

\[
F_v = \begin{cases} 
-P_{uc} + k_{EJuB}(\Delta u - \Delta l_{EJB}) & \Delta l_{EJB} + P_{uc}/k_{EJuB} \leq \Delta u \leq \Delta l_{EJB} \\
-P_{uc} + k_{EJuB}(\Delta u + \Delta l_{EJB}) & \Delta l_{EJB} + P_{uc}/k_{EJuB} \leq \Delta u < -\Delta l_{EJB} \\
0 & \Delta l_{EJB} + P_{uc}/k_{EJuB} \leq \Delta u < l_{EJ} \\
\pm F_b & |\Delta \nu| \geq \Delta w_{EJB} \\
\end{cases}
\]
in which $F_b$ : friction force of an expansion joint after failure and $k_{EJuB}$: post buckling stiffness of an expansion joint. Assuming that the axial restoring force of the fingers sharply deteriorates once the fingers buckle under compression in the longitudinal direction, $k_{EJuB}$ is evaluated as

$$ k_{EJuB} = -k_{EJu} \quad \text{(13)} $$

### 3. IDEALIZATION OF A TARGET BRIDGE

To study the effect of expansion joints on the seismic response of a bridge, the above analytical model for an expansion joint was implemented to a three-span simply supported bridge (D2, D3 and D4) as shown in Fig. 3. Effect of the adjacent decks (D1 and D5) was approximately taken into account in analysis by lumping half of the mass of D1 and D5 at the top of P1 and P4, respectively. The structural parameters of the target bridge are derived from reference (13). A 40-meter long and 12-meter wide deck with a mass of 628 t each is supported by 6-14 m tall cantilevered reinforced concrete piers. The gap between each deck is 0.2m. The axial stiffness of a deck is $1.217 \times 10^8$ kN and the columns are supported by pile foundations. Type II (moderate) soil condition was assumed based on the JRA design code and it was further assumed that liquefaction does not occur. A pile foundation including the soil-structure interaction was idealized by a set of translational and rotational springs under the footing. The superstructures are supported by elastomeric bearings. The piers are idealized by fiber elements at their plastic hinge regions. The lateral confinement of concrete including unloading and reloading paths was idealized by Hoshikuma et al. and Sakai and Kawashima models. The piers section outside of the plastic hinge zone and the lateral beams were idealized by elastic beam elements. The effect of damping was included in the analysis in terms of Rayleigh damping. After evaluating the model damping ratios based on the strain energy proportion method, assuming the element damping ratio of the decks, piers and foundations of 2%, 5% and 20%, respectively, two parameters of the Rayleigh damping were determined so that the damping ratio between the 1st and the 23rd mode become approximately 2%. The computer program “TDAP III” was used for the
Expansion joints consisting of one hundred twenty-0.275 m long, 66 mm wide and 40 mm high fingers were assumed\(^{18,19}\). The gaps between adjacent fingers, \(E_{Jl}\) and \(E_{Jw}\), are 0.135 m and 0.005 m, respectively. The effective length of fingers in the longitudinal direction \(E_{Jel}\) is 0.14 m. The parameters in Eqs. (8)-(10), Eq. (13) and Eq. (16) are set as \(E_{Jvk}=2.89 \times 10^6 \text{kN/m}\), \(E_{Juk}=4.61 \times 10^8 \text{kN/m}\), \(E_{Juok}=2.35 \times 10^8 \text{kN/m}\), \(E_{JuBk}=-4.61 \times 10^8 \text{kN/m}\) and \(l_{uk}=L_{vk}=4.61 \times 10^8 \text{kN/m}\), and the parameters in Eqs. (3)-(5) are \(v_P=6.65 \text{MN}\), \(u_P=275.5 \text{MN}\), and \(u_{uc}=551 \text{MN}\). The fault normal and parallel components of JR Takatori Station record (refer to Fig. 4) during the 1995 Kobe, Japan earthquake were imposed to the bridge in the longitudinal and transverse directions, respectively.

4. SEISMIC RESPONSE WITHOUT LOCK-UP OF EXPANSION JOINTS

Fig. 5 shows response displacements and accelerations of D3 at P3. The responses of D3 disregarding the effect of expansion joint in the analysis are also shown in Fig. 5 for comparison. The response displacements of D3 by disregarding the effect of expansion joints are 0.684m and 0.576m in longitudinal and transverse directions, respectively. On the other hand, response displacements of D3 became 0.543m and 0.564m in the longitudinal and transverse directions, respectively, if the effect of expansion joint is included in the analysis. Thus, the longitudinal response displacement of D3 decreases by 21% by including the effect of expansion joints in the analysis. However, there is no substantial change in the transverse response displacement. The peak longitudinal and transverse response accelerations increase from 10.93 m/s\(^2\) and 15.41 m/s\(^2\) to 1770 m/s\(^2\) and 41.5 m/s\(^2\) by including the effect of expansion joints. As will be described later, the significant increase of the peak response accelerations resulted from the pounding between fingers.

Fig. 6 shows details of the response acceleration shown in Fig. 5 between 0 and 10 s. Only the response acceleration less than 20 m/s\(^2\) is shown here by eliminating high acceleration pulses. As is obvious from Fig. 6, the response acceleration computed by taking account of the effect of expansion pulses is close to that computed by disregarding the effect of expansion joints if high pulses are eliminated. The pulses with high peak accelerations occur more...
frequently in the longitudinal response, because transverse gap $\Delta w_{EJ}$ which is much smaller than the longitudinal gap $\Delta l_{EJ}$ develops smaller pounding force.

Fig. 7 (1) compares the response displacement between D2 and D3. It is important to note that the longitudinal relative displacement of expansion joint $\Delta u$ keeps a value of approximately 0.14m between 3.35s to 7.19s if the effect of expansion joint is considered in analysis. It is also noted that the transverse relative displacement of expansion joint $\Delta v$ does not significantly change by including the effect of expansion joint in analysis. Fig. 7 (2) shows the corresponding restoring forces at the expansion joint between D2 and D3 when the expansion joints are considered in analysis. While the peak restoring force at the expansion joint between D2 and D3 is 6.65 MN at 7.213s in the transverse direction, extremely large pounding forces over 50 MN occur several times in
the longitudinal direction due to collisions at the expansion joint.

Focusing on the responses between 0 to 10 s, the displacements and restoring forces presented in Fig. 7 become as shown in Fig. 8. Between 0 to 3.35 s, whenever the transverse relative displacement of the expansion joint $\Delta v$ reaches the gap of fingers $\Delta w_{EJ}$ (= 0.005m), a restoring force $F_v$ as large as 1.4 MN develops. On the other hand, in the longitudinal direction, tips of the fingers collide with the bases of the other side fingers at 2.81 s resulting in a longitudinal compression force $F_u$ of 43.9 MN. Then the fingers are subjected to tension, and they completely slip out ($\Delta u \geq l_{EJ}$) at 3.35 s. Because this enables the expansion joints to freely displace in the transverse direction, the transverse relative displacement of the fingers $\Delta v$ starts to exceed the transverse gap $\Delta w_{EJ}$ (= 0.005m) at 3.35 s. Once the fingers slip out longitudinally and displace transversely larger than $\Delta w_{EJ}$, the fingers can freely move longitudinally and transversely, but they cannot slip into the original contact position no matter how they are subjected to compression. Consequently, the fingers repeatedly contact and separate due to rebound at their tips resulting in 14 times collision and separation until 7.19 s. It is the reason why longitudinal relative displacement $\Delta u$ keeps nearly 0.14 m between 3.35 s and 7.19 s. The maximum pounding force during this stage is 99.5MN.
The transverse relative displacement of expansion joint $\Delta v$ becomes smaller than the transverse gap of the expansion joint $\Delta w_{EJ}$ at 7.20 s, hence the fingers returned to their original contact position. Subsequently, because the transverse restoring force of the expansion joint $F_v$ reaches the transverse strength $P_v$ (= 6.65 MN), the expansion joint ruptures in the transverse direction at 7.213 s, and it also loses the function in the longitudinal direction. Following Eqs. (11) and (12), the expansion joint transfer only the friction force $F_b$ in the longitudinal and transverse directions after its failure.

Fig. 9 shows the restoring force vs. relative displacement hysteresis of the expansion joint between D2 and D3. In the longitudinal direction, $\Delta u$ and $F_u$ reaches -0.135 m and 43.9 MN, respectively, due to collision between the tips of fingers and the bases of the other side fingers. The compression force induced at $\Delta u$ =0.14 m results from collision between the tips of fingers after they once slip out and start to contact. On the other hand, in the transverse direction, the large relative displacement $\Delta v$ of -0.23 m and 0.22 m results from free movement of the expansion joint after their rupture.

As shown above, the expansion joint between D2 and D3 ruptured transversely. However, because the expansion joint between D3 and D4 did not rupture, the responses at this expansion joint are shown in the following for comparison with the above results.

Response displacements and resultant restoring forces of the expansion joint between D3 and D4 are shown in Fig.10. Fig.11 shows detailed responses focusing on the displacements and restoring forces between 2 s to 8 s. It is seen in Figs. 10 and 11 that similar to the expansion joint between D2 and D3, the expansion joint between D3 and D4 cannot slip into the original contact position after they once longitudinally slipped out and transversely displaced over $\Delta w_{EJ}$ for three times (between 3.53 and 3.61 s, 4.82 and 5.25 s and 6.35 and 6.60 s). Because the expansion joint between D3 and D4 maintained its function without rupture, the transverse relative displacement of expansion joint $\Delta v$ is much smaller than that at the expansion joint between D2 and D3.

Fig. 12 shows the restoring force vs. relative displacement hysteresis of the expansion joint between D3 and D4. The smaller transverse relative displacement $\Delta v$ is obvious compared to the hysteresis of the expansion joint between D2 and D3 (refer to Fig. 9).

Figs. 13 and 14 show the response displacement at the top of P3 and the moment vs. curvature hysteresis of P2 at the plastic hinge, respectively. In the transverse direction, the effect of expansion joints is less significant on the column response displacement...
and the moment vs. curvature hysteresis, because the restraint of the expansion joints to the relative displacement $\Delta v$ does not affect the column response displacement whereas it reduces the relative displacement $\Delta v$. On the other hand, the effect of expansion joints is significant in the longitudinal direction. The peak response displacement at the top of P2 is 0.316 m if the effect of expansion joints is included in the analysis, and it is 65.3% of the peak column response displacement computed by disregarding the effect. Consequently, the peak curvature at the plastic hinge reduces by 40% from $33.5 \times 10^{-3}$ 1/m to $20.1 \times 10^{-3}$ 1/m by considering the effect of expansion joints.

5. SEISMIC RESPONSE WITH LOCK-UP OF EXPANSION JOINTS

In the above analysis, it was assumed that the expansion joints transfer only the friction force once they fail. Consequently, the expansion joints which failed have similar functions with the energy dissipators in seismic isolation. However the function of an expansion joint which suffers extensive damage under extreme ground motions is not so simple. It is often the case that fingers were badly deformed and bent resulting in locking the relative displacements $\Delta u$ and $\Delta v$.

Fig. 15 shows the response displacement at the top of P2 and Fig. 16 shows the response displacements and response accelerations of D3 at P3. The expansion joint between D2 and D3 fails and locks-up at 7.213 s. The effect of lock-up is apparent in the responses after 7.213 s. For example, virtually no residual displacement (permanent drift after the excitation is completed) occurs at the top of P2 if the expansion joints do not lock-up; however it increases to 0.08 m if the expansion joints lock-up. Because it is specified in the design code that the residual
displacement shall be less than 1 % of the column height\(^{14}\), the residual displacement of 0.08 m corresponds to 67 % of the design residual displacement. The residual displacement at the top of P3 results in the residual displacement of 0.05 m at D3. It is significantly larger than the residual displacement of 0.01 m which is computed at D3 by disregarding the effect of lock-up of the expansion joints.

**Fig. 17** considers the D3 response acceleration on P3 (refer to **Fig. 16 (2)**) between 0 and 13.0 s by eliminating the response accelerations over 20 m/s\(^2\). Reminding that the expansion joint failed at 7.213 s, it is seen in **Fig. 17** that high pulse accelerations are developed between 2.18s and 7.213s due to poundings between the tips and bases of fingers in the longitudinal direction. After the expansion joint fails at 7.213 s, extremely high pulse accelerations are not developed in the deck response acceleration.

**Fig. 18** shows the response displacement and resultant restoring force of the expansion joint between D2 and D3. **Fig. 19** shows enlarged response of **Fig. 18** between 0 and 10 s. It is seen that the longitudinal and transverse relative displacements, \(\Delta u\) and \(\Delta v\), are 0.138 m and 0.006 m, respectively at the instance when the expansion joint fails (7.213 s), and \(\Delta u\) and \(\Delta v\) are locked at those relative displacements if the lock-up of expansion joints is considered in analysis.

**Fig. 20** shows the effect of lock-up of the expansion joints on the moment vs. curvature hysteresis of P2 at the plastic hinge. The effect of the lock-up on the peak moment and peak curvature is not significant, however, a large residual curvature is developed in the longitudinal direction associated with the residual displacement of P2 as described earlier.
6. CONCLUSIONS

A nonlinear hysteretic model of steel finger-type expansion joints was developed to investigate the effect of finger expansion joints on the seismic response of bridges and the proposed model was implemented to an analysis of a three-span simply supported plate girder bridge. Although experimental verification for the evaluation of the strength and deformation properties of expansion joints is required, the following conclusions may be deduced from the analytical results presented herein.

1) The bridge seismic response is constrained by the complex mechanism of expansion joints including constraint by fingers, pounding, slip-out, failure and lock-up. The effect of expansion joints is significant on the seismic response in the longitudinal direction.

2) Between the two failure models of expansion joints developed in this study, the model which assumes that expansion joints lock after failure results in more significant effect on the seismic response of the bridge than the model which assumes that the expansion joint only transfer the friction force after failure. This is because the relative displacement between the adjacent decks is more significantly restrained in the model which takes account of the lock-up.

3) The effect of expansion joints is significant on the plastic deformation of the columns, response displacement of the decks and columns and the residual displacement. Consequently, it is important to consider the realistic hysteretic behavior of the expansion joints in the seismic response analysis of bridges.

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