ACOUSTIC EMISSION MONITORING FOR ASSESSMENT OF STEEL BRIDGE DETAILS

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ABSTRACT. Acoustic emission (AE) testing was deployed on details of two large steel Interstate Highway bridges: one cantilever through-truss and one trapezoidal box girder bridge. Quantitative measurements of activity levels at known and suspected crack locations were made by monitoring AE under normal service loads (e.g., live traffic and wind). AE indications were used to direct application of radiography, resulting in identification of a previously unknown flaw, and to inform selection of a retrofit detail.

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INTRODUCTION

Cracking is an important deterioration mode for steel bridges. However, not all cracks warrant the same concern — in fact, certain crack types are quite likely to be self-extinguishing [1]. Acoustic emission (AE) monitoring is a useful technique for distinguishing active and extinguished cracks in steel bridges, particularly because AE energy is released under normal service loads.

Acoustic emission can be a valuable technique for detecting fatigue cracking. Simple observation of changes in count rate can be a useful metric. Even though these events may come from either crack extension itself, localized plastic deformation around the crack tip [2], or from fretting of surfaces in the crack wake, the exact mechanism is not of great importance to the structural engineer — knowledge that a crack is propagating or extinguished is sufficient.

Growth of fatigue cracks can be approximated by the Paris law [3]:

$$\frac{da}{dN} = C(\Delta K)^m \tag{1}$$

where da/dN is crack extension per cycle, ΔK is the cyclic variation in the stress intensity factor, and C and m are material parameters. It has been shown [2] that a relationship similar to the Paris law may be used to relate AE count rate to the cyclic stress intensity factor range:

$$\frac{d\eta}{dN} = B(\Delta K)^p \tag{2}$$

where $d\eta/dN$ is the number of AE counts per load cycle and B and p are material constants. This seems to be a useful relationship in both the laboratory and the field. Roberts and Talebzadeh [4] found good agreement between Equation (2) and experimental results in tests of compact tension and welded T-girder specimens of Grade S275JR steel, a European mild structural steel roughly equivalent to ASTM A36, a common material for steel bridges. Similarly, Gong et al. [5] made AE observations of fatigue cracks on 36 steel railroad bridges and used a crack safety index based on Equation (2) to identify active cracks.

Since AE propagates well in steel plates — and most steel sections used in bridge construction can be reasonably modeled as plates — an AE transducer array circumscribing an area of tens of square feet can detect any AE emanating from a flaw, regardless of the flaw's precise location. Analysis based on hit rates and location algorithms can then provide insight into crack behavior. Other NDE techniques, such as ultrasonic testing and eddy current testing, require direct access to the crack area, and therefore *a priori* knowledge of the precise location of the crack.

CASE STUDY: CRACK CHARACTERIZATION

The John F. Kennedy Memorial Bridge, a large cantilever through truss opened in 1963, carries Interstate 65 across the Ohio River at Louisville, Kentucky. Inspection revealed a 5" long full-depth transverse crack in a tension region of the top chord of the upstream truss. The chord is a welded I-section on its side, such that the web is oriented horizontally and the two flanges are vertical; the crack was in the horizontal web. A partial-depth saw cut and an irregularly-shaped hole of unclear origin were present along the web-flange weld, and a one-inch diameter stop hole was present at the end of the crack, as shown in Fig. 1.

The crack is in a fracture-critical member, meaning that failure of member would likely result in partial or complete failure of the bridge. AE monitoring was employed in conjunction with other non-destructive evaluation techniques, including ultrasonic testing and radiography, to help detect and characterize any indications that the crack might jump the stop hole or propagate into the vertical flange. A six-channel AMSY-5 acoustic emission system with 150 kHz-resonant piezoelectric transducers (Vallen Systeme GmbH, Icking, Germany) was used for the tests. Transducer 1, the "crack" transducer, was deployed at the stop hole, and Transducers 3–6 were deployed in a rectangular array around it. These transducer locations are shown in Figure 1. Transducer 2 was deployed outside the rectangular array on the vertical flange to intercept noise from a nearby bolted splice.

Planar Location Analyses

Planar location analysis on the horizontal web was performed using AE time-of-

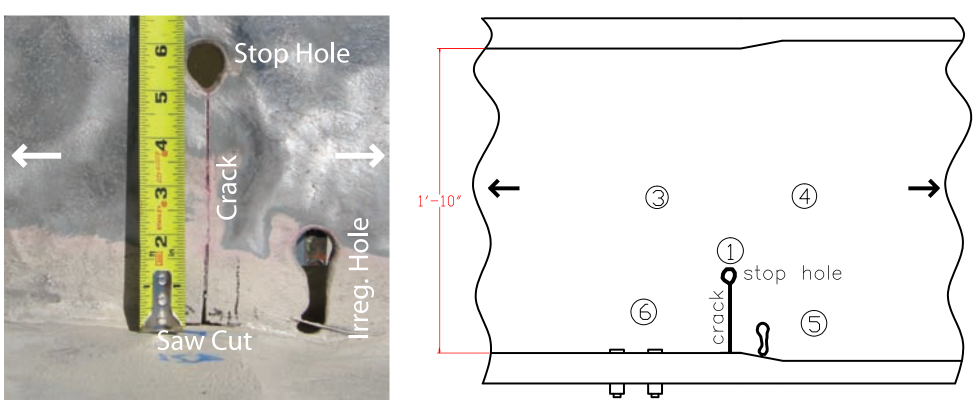


FIGURE 1. Annotated photograph (looking down) and drawing of flaws on horizontal web of top chord: 5" long transverse crack, stop hole, partial-depth saw cut, and irregularly-shaped hole. Circled numbers represent transducer locations. Heavy arrows indicate axial tension in the member.

arrival differences from Transducers 1–6. Transducer 2, deployed on the vertical flange, outside the planar array, was used as in combination guard/normal mode; that is, events producing a first hit on Transducer 2 were rejected outright, while events producing second or third hits on Transducer 2 were accepted and located. This first-hit channel filter was particularly important because it rejected noise from a nearby bolted splice. Location analysis was complicated by the presence of the crack and stop hole — these discontinuities were large relative to the wavelength of AE signals. AE source location is based on differences in signal arrival time between different sensors, and requires the assumption that direct acoustic paths exist from the AE event to each transducer used in location. The first location analysis was based on arrival times from all transducers, neglecting the crack and stop hole, but two alternate location analyses — one based upon Transducers 1, 3, 6, and the other on Transducers 1, 2, 4, 5 — were also run. In these sub-arrays, the web was free from large discontinuities; thus, the assumption of continuous plate held. Significantly, the results of the three location analyses complement each other: comparison locations results reveals that most events located using the whole array are corroborated by the sub-arrays.

Cluster Analysis

Cluster analysis provided helpful insight into the acoustic emission behavior of the horizontal web. The clustering technique was originally developed for welding process monitoring [6]. Clustering is based upon the premise that cracks and other flaws tend to be active, highly localized acoustic emitters, while emissions from other sources, such as movement of dislocations, tend to be randomly distributed. Thus, a number of AE events detected in a highly localized cluster — for example, a group of events in a one-inch radius — likely indicate the presence of a flaw, while the same number of events distributed randomly over a one-foot radius would be less likely to indicate a flaw. Since cluster analysis depends upon location analysis, the same geometric challenges discussed the preceding section applied to clustering. Cluster analyses were therefore performed using planar location results based upon Transducers 1–6, Transducers 1, 3, 6, and Transducers 1, 2, 4, 5. The results are shown in Figs. 2, 3a, and 3b, respectively.

The three analyses identified tight clusters at two points on the horizontal web. These clusters of located events are circled in Figs. 2 and 3. Subsequent radiography of these points confirmed the presence of a flaw at the cluster between the crack and the irregularly-shaped hole, which was the more active emitter. This flaw is believed to be a slag inclusion. Inclusions in rolled steel sections are known to be active acoustic emitters, often due to fracture of the inclusion itself [7].

Notes on Location and Cluster Analysis

The planar location algorithm upon which the cluster analysis depends is conceptually straightforward and mathematically convenient, but it does not account for uncertainty or errors in important inputs to the location calculation, such as propagation velocity and placement of transducers. Based exclusively upon the wavelength involved, AE measurements at 150 kHz could theoretically resolve locations within 0.0013 inches ($\lambda = \frac{v_p}{f} = \frac{189\mathrm{in/sec}}{150\ \mathrm{kHz}}$). In practice, the authors' observations with pencil lead breaks on an isolated steel plate suggest that calculated planar locations are typically within a half-inch radius of the true location.

One approach to extracting more meaningful results from location and clustering in light of uncertainty is to analyze clusters in both space and time. The cluster analyses above considered only two-dimensional location: any group of events within one inch of each other was counted as a cluster. Analysis can be improved by taking time into account — for example, considering events to be a cluster only if they occur within one inch of each other

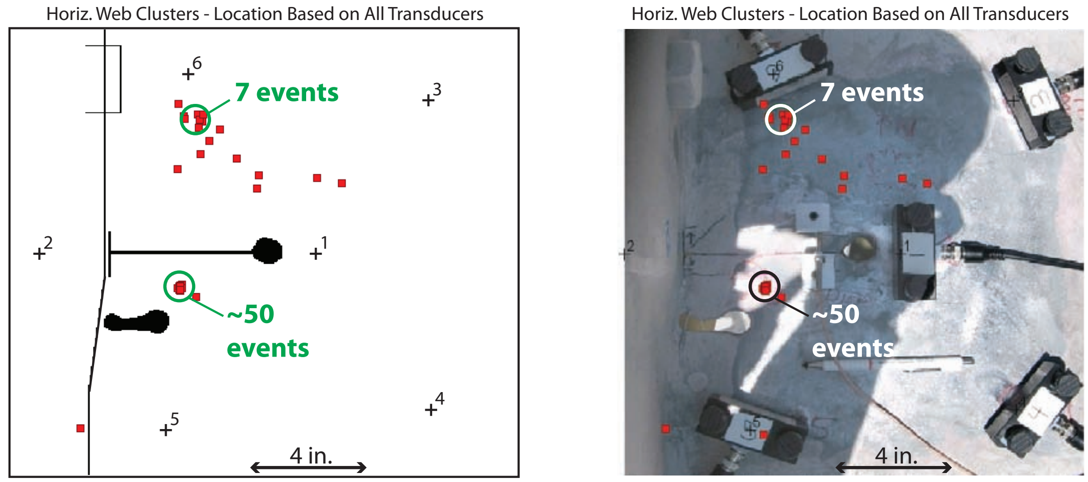
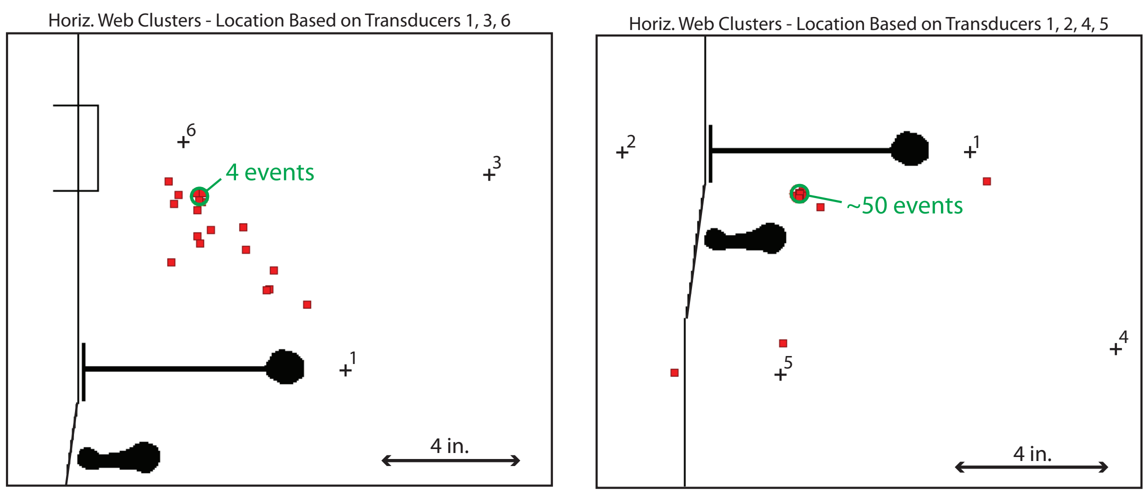


FIGURE 2. Clusters of AE events on horizontal web, using location results based on all channels. Individual located events are indicated by box icons. Transducer 2 was used in combined mode; events producing first hits on Transducer 2 were rejected outright, but events producing subsequent hits on Transducer 2 were located. Clusters of events are circled.



(a) Location based on Transducers 1,3,6

(b) Location based on Transducers 1,2,4,5

FIGURE 3. Alternate cluster analyses on horizontal web. Individual located events are indicated by box icons. Clusters of events are circled.

in space and one second of each other in time (recalling that flaws tend to be active emitters likely to produce high hit rates). While planar location depends on very precise time-of-arrival measurements (the system clock on the AE monitor used here can resolve 1 μs), temporal clustering depends on time-of-arrival measurements with resolution five or six orders of magnitude larger, requiring much less precision. As such, the confidence that events occurred within a given time of each other is much higher than the confidence in their location results. Given that reported locations on a steel plate are likely to be within a half-inch radius of the true source locations, and recalling that flaws tend to be active emitters likely to produce high hit rates, combined spatial-temporal clustering can improve the likelihood that clusters accurately represent real physical phenomena.

Kennedy Bridge Crack Characterization Conclusions

In the case study, the AE location and cluster analysis revealed no indication that the crack had propagated into the vertical flange in the area of interest. There were no AE indications that the crack had jumped the stop hole. Cluster analysis did show indications of a flaw in the horizontal web. The presence of this flaw, which is believed to be a slag inclusion, was later confirmed by radiography. Corroboration of AE results by other well-established non-destructive evaluation techniques helps validate the use of AE for evaluation of cracks in steel bridge details.

CASE STUDY: RETROFIT EVALUATION

Retrofit evaluation by acoustic emission was performed on the Bryte Bend Bridge, which carries Interstate 80 over the Sacramento River at Sacramento, California. Each of the twin bridges consists of 22 welded trapezoidal steel box girder spans with composite concrete decks. The box girders are fracture-critical members. Inside each box girder are stiffener cross frames with K-shaped interior struts. Cracking of the box girder web near these details was discovered during inspection. Cracks typically initiated at the toe of the weld connecting cross frame to the bottom of the web. The cracking was attributed to out-of-plane bending at the connection. These cracks were of concern particularly because the box girder is a monolithic welded structure — according to California Department of Transportation (Caltrans) engineers, the only geometric or material feature to prevent cracks from propagating from the web to the bottom flange (the critical tension element) was the heat-affected zone at the toe of the weld.

Because of the complex stress field at the details, it was difficult to predict the performance of proposed retrofit designs. Furthermore, because over one thousand instances of the fatigue-prone details were present on the bridge, it would be extremely expensive to re-retrofit the details should the retrofit fail to mitigate fatigue cracking. Caltrans engineers opted to test two different retrofit prototypes *in-situ* on similar areas of the bridge to determine their fatigue-mitigation effectiveness. Because much of the bridge is composed of identical simple spans, it is reasonable to take one or two spans as representative of much of the whole bridge.

Quantifying Crack Activity at Retrofit Sites

The first acoustic emission tests at Bryte Bend were conducted in 1993–94 by Prine and Marron [8] at sites selected by Caltrans. First-hit channel (FHC) acoustic emission analysis was employed to distinguish emissions from the crack from emissions originating elsewhere on the structure. For FHC analysis, one transducer was placed at the visible crack tip and an array of guard transducers was installed around it. In post-processing, all AE events that produced a first hit on the crack transducer were counted as events originating at the crack, and events that produced a first hit on one of the guard transducers were counted as events originating elsewhere. The AE data, along with complementary strain gage measurements, were interpreted to indicate that the cracks were actively driven by live stresses in the structure [8].

Two prototype retrofits were designed by Caltrans engineers. Each was tested on selected cross frames on a representative span of the bridge. In Design 1, shoe plates and knee braces were added at the web-flange corners. Design 2 featured the same shoe plates and knee braces; additionally, the diagonal braces were cut from their attachment points at the underside of the deck and reattached to a new horizontal cross member.

In 1996, combined AE and strain gauge testing was employed in the evaluation of these retrofit designs. First-hit channel analysis was employed to distinguish crack-related events from events originating elsewhere on the structure. The activity level for each crack is given as the ratio (expressed as a percentage) of crack-related AE hits to total recorded AE hits [8]. The activity level at each crack is shown in Fig. 4.

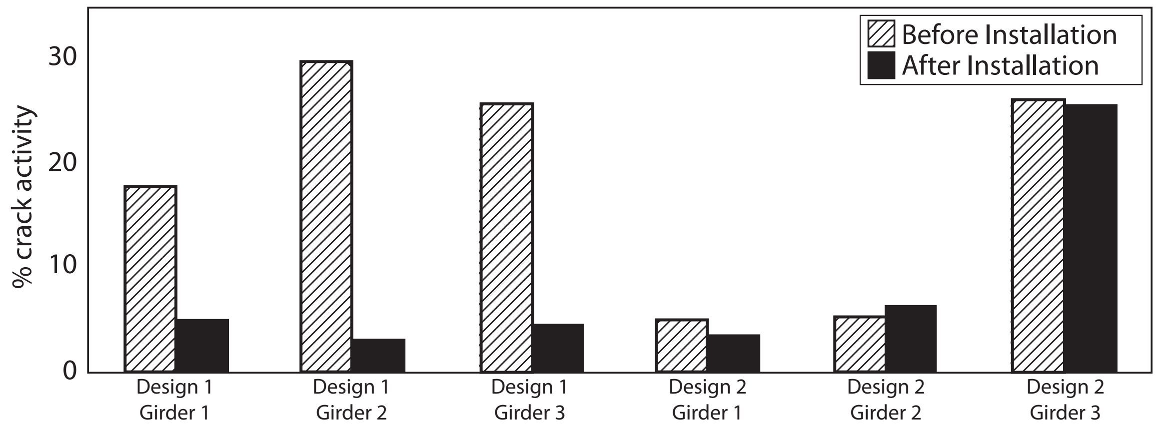


FIGURE 4. Crack activity at prototype retrofit sites (modified from Prine and Marron [8])

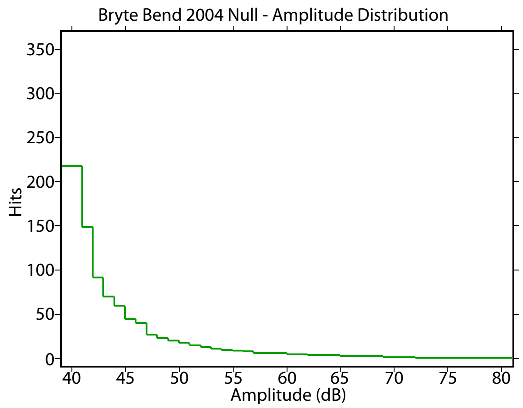
The Design 1 retrofit prototype was clearly shown to be superior to Design 2. In fact, Design 2 seemed to increase the crack activity level slightly on the Girder 2 web connection. The value of AE testing is clearly illustrated in this prototype evaluation experience. On a complex structure, it is often difficult to predict the performance of a retrofit accurately. AE analysis, however, provides repeatable quantitative data on crack activity levels before and after a fatigue-mitigation retrofit.

In 2004, Caltrans let contracts to retrofit all active and potential crack sites with retrofit Design 1; pre- and post-retrofit AE tests were conducted to quantify overall retrofit performance. Again, FHC analysis was used, with Transducer 1 as close as possible to the crack tip, Transducers 2–5 forming a guard array around the crack tip, and Transducer 6 mounted on the diagonal brace to intercept any noise transmitted through the cross frame itself. The AE array geometry is shown in Fig. 5.

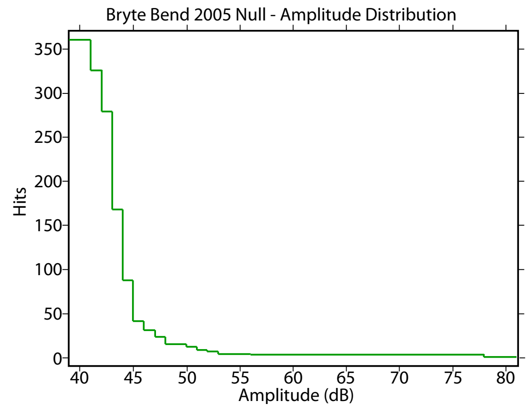
Ensuring Valid Comparison Between Tests

AE tests were conducted at five selected sites on a representative span in September 2004, before the retrofit, and again in September 2005, after the retrofit. While it is impossible to control live traffic loading without closing the bridge, all reasonable steps were taken to mitigate external factors that might affect test results: tests were conducted at the same time of year (an important factor due to ambient temperature and the seasonal nature

FIGURE 5. AE transducer array for first-hit channel analysis of fatigue-prone detail during post-retrofit test



(a) Pre-retrofit (2004)



(b) Post-retrofit (2005)

FIGURE 6. Amplitude distributions from Bryte Bend pre- and post-retrofit null tests, showing comparable levels of overall AE activity

of heavily-loaded agricultural trucking using the bridge), at roughly the same times of day, during similar weather conditions. All tests had similar durations of thirty to sixty minutes.

AE "null" tests were conducted to quantitatively demonstrate that the 2004 and 2005 tests were comparable. In these null tests, an AE array with geometry similar to the FHC array described above was deployed on an area of the girder web distant from any cross frames, access panels, bearings, or any other details. The amplitude distributions for first hits on Channel 1 in Fig. 6 show that the overall AE activity levels on the bridge were comparable between 2004 and 2005; if anything, the 2005 null test showed greater activity.

Bryte Bend Bridge Retrofit Evaluation Conclusions

FHC analysis of the data taken before and after the full retrofit suggests that the retrofit was quite effective in reducing fatigue crack growth. Each site showed a dramatic decrease in crack activity as measured by the number of AE hits from the crack with peak amplitude above 55 dB per hour, as shown in Fig. 7.

Because AE hit rates and amplitudes can be related to cyclic stress ranges, comparison of AE parameters before and after a retrofit can provide quantitative empirical indication of changes in the cyclic stress range; the greater the decrease in hit rate and amplitude, the more

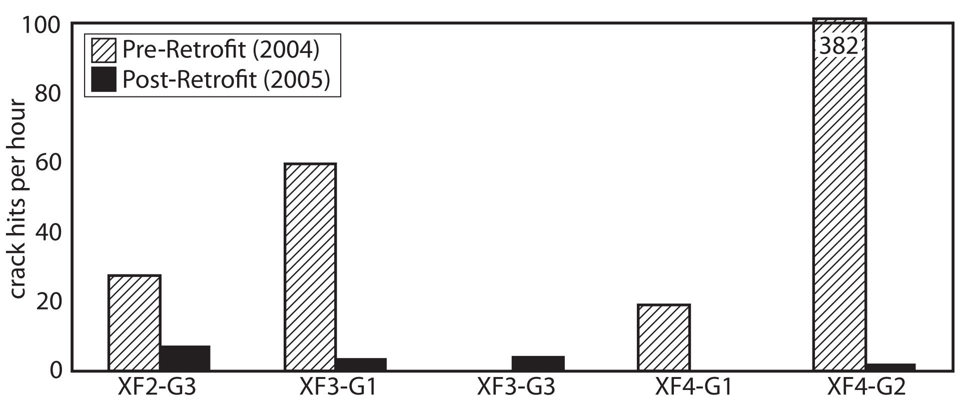


FIGURE 7. Crack activity (first hits with amplitude > 55 dB per hour) before and after full retrofit on girder webs G1, G2, G3 and cross frames XF2, XF3, XF4

successful the retrofit. In the case of the Bryte Bend Bridge, AE was successfully employed several times to aid in the characterization of cracks, development of an effective retrofit design, and finally in the evaluation of a complete fatigue retrofit of the structure. Without the feedback provided by AE testing, much time and effort probably would have been wasted testing ineffective retrofit designs.

CONCLUSIONS

By nature of the technique, acoustic emission testing is well suited to the problem of characterizing cracks in steel bridge details as actively growing or extinguished. The stress field in a steel bridge detail is often very complicated, containing highly localized stress concentrations. While other techniques, such as ultrasonic testing, require up-close access to the crack itself, AE testing can locate and characterize a crack within a more general area, making it a more forgiving method in terms of access and precision with which a crack must be located prior to testing. This should not be taken to mean that an entire bridge may be examined for cracks with only a few AE transducers — acoustic noise from riveted or bolted connections and wind-blown dust, plus electrical noise from long instrument cables make that impractical. Rather, AE is best used to monitor areas of a few tens of square feet in complex, high-stress regions such as connections.

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