Rehabilitation of Blue Nile Steel Bridge Superstructure: Fatigue Assessment

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مستخلص: جسر النيل الأزرق الحديدي يقع على نهر النيل الأزرق بولاية الخرطوم، الجسر في الخدمة زهاء 112 عاماً . الجسر عبارة عن جملون حديدي مبرشم من فئة بيتيت وله سبعة أبحر بطول 65.53 متر و بحر له رافعة متحركة، السعة الحالية للجسر ما يقارب حوالي 61,000 سيارة يومياً بالإضافة للقطارات و المشاة. خلال الأعوام من 1960 م حتى 2014 م تم إجراء عدة دراسات لتقييم حالة الجسر الإنشائية بواسطة جهات عديدة ، حيث أوضحت هذه الدراسات أنه نسبة للتحميل الدوري خلال فترة زمنية طويلة بالإضافة للتأثيرات الخاصة بالبيئة المحيطة سواء كانت طبيعية أو بفعل الإنسان ، فإن جسم الجسر لحق به ضرر جسيم مما يتطلب إجراء الصيانة الوقائية، و الذي تم التخطيط لها بغرض زيادة العمر التصميمي للجسر لمدة 50 عاماً أخرى. الصيانة أجريت في الفترة من (2017 - 2018) م. هذه الورقة تقدم جسر النيل الأزرق الحديدي كدراسة حالة و تتضمن سرد للدراسات السابقة في تقييم الكلال للأعضاء الحديدية المتآكلة و العارضات الطولية الحاملة لقضيب السكة الحديد، و توضح الورقة البرنامج المقترح لصيانة الأعضاء المتضررة بالجسر كما تتطرق للتحديات التي يمثلها الجانب التصميمي الخاص بتقييم إجهاد الكلال، تم استخدام برنامج ميداس سيفيل 2006 و برنامج ميداس فيا 2016 لتحليل الكلال في الأعضاء المتضررة باستخدام طريقة العناصر المحددة و لتقدير العمر المتبقى للكلال تم تطبيق النظرية الكلاسيكية و ذلك من أجل تحديد مدى تأثير الإجهاد على تلك الأعضاء ومدى سلامتها مستقبلاً . وُجد أن الضرر التراكمي الإجمالي أكبر من 1. عليه، يمكن إستنتاج أن العمر المتبقى للكلال الخاص بالأعضاء الحرجة قد نفذ. يعتبر تقوية الأعضاء الحرجة كأكثر حل ملائم للمشكلة.

ABSTRACT The Blue Nile Steel Bridge over the Blue Nile River in Khartoum, Sudan, has been in service for 112 years. A riveted steel through-truss of Pettit Configuration with seven equal fixed spans of 65.53 m and a rolling lift span. The bridge currently accommodates approximately 61,000 vehicles per day along with insignificant pedestrian and railway traffic. Over the years from 1960 to 2014 several assessment studies were carried out by numerous parties have revealed that under cyclic loading of a long period time and effects of natural and man-made disasters, bridge deck was damaged severely and needed to be repaired and strengthened. A rehabilitation program was planned to extend the design life of the bridge for a more 50 years, which was carried out in period (2017 - 2018). This paper presents as a case study including a literature review on fatigue assessment of stringers on railway track. The rationale for selecting the rehabilitation strategy for the bridge is described, highlighting the challenging design aspects related to fatigue assessment, clarifying the methodology in which main members were identified for strengthening, using Midas Civil 2006 v7.01 and Midas FEA 2016 v1.1 software to analyze the fatigue in the critical members by generating a model using Finite Element Method and estimating remaining fatigue life by adopting the classical approach (Stress-life method), the total damage accumulation was found greater than 1. Thus, it can be concluded that the stringers have no remaining fatigue life. Strengthening the stringers is considered the most favorable solution.

Keywords: AASHTO, Assessment, Crack, Failure, Fatigue, Old steel bridges, Rehabilitation, Replacement, strengthening.

1 INTRODUCTION

Fatigue is a localized and progressive structural damage in which caused by a repetitive, fluctuating cyclic loading such as vehicles for steel bridges. The damage accumulates over a sustainable period of time. Ultimately leading to fracture and failure of the structural component. Since Fatigue is responsible for 80% to 90% of failures in old steel structures and 13% of failures in overall steel bridges, Fatigue has emerged as one of the major concerns associated with old steel railway bridges as shown in Fig. 1 [1][2]. Due to the adverse consequences of failure in terms of human lives loss and economic ramifications, it is imperative to evaluate the remaining fatigue life of old steel bridges to ensure a safe service.

Fig. 1: Failure modes associated with steel bridges collapses.

The Blue Nile Bridge was built in 1909. The Bridge is a riveted steel through-truss of Pettit Configuration with seven equal fixed spans of 65.53 m and a rolling lift span. It was originally designed as a railway bridge as illustrated in Fig. (2).

Fig. 2: The Blue Nile Bridge under construction (1909), <https://sudaneseonline.com/cgi-bin/sdb/2bb.cgi?seq=print&board=13&msg=1241742863&rn=550>

It is reckoned that to identify the most critical and fatigue prone steel member in the superstructure, a fatigue assessment is required.

To evaluate fatigue resistance of old steel bridge and establish fatigue categories, this paper will discuss and verify the fatigue evaluation by using an effective Finite Element model (FEM) generated by Midas Software Civil 2006 Version 7.01 and Midas FEA 2016 Version 1.1, Midas Information Technology Co. Ltd, Seoul.

2 BACKGROUND AND PREVIOUS INVESTIGATIONS

A. Background

The Blue Nile Steel Bridge is constructed by the Cleveland Bridge Colt in 1907 -1909 under the authority of Sudan Railway Corporation (previously known as Sudan Government Railway). It was built originally for the purpose of extending the railway system southward towards Sennar [3].

The bridge has a total length of 558.93 m between bearings on abutments, and an overall width of 16.05m, with 11.76 m between centers of trusses. The clear width between trusses is 10.98m, made up of a clear 4.57m passage for the railway track, a clear 6.40m for the roadway on the downstream (abbreviated as D/S) side and a 3.35m footway cantilevered outside the west (D/S) trusses as shown in Fig. s (3) and (4)[4].

Fig. 3: A Photo of the Blue Nile Bridge (2014).

In October 2017, State of Khartoum government had closed the Bridge prior to rehabilitation of bridge superstructure for the purpose of strengthening and rehabilitation of bridge members such as:

- Corroded troughs and steel arches and other steel members of the deck.
- Plate girders of approach spans and vertical stiffeners.
- All C-channels on motorway adjacent to the railway section.
- Wood planks on lift span deck as they were

removed and replaced by reinforced concrete deck after adding new troughs on both sides of the deck.

- Sandblasting and repainting with three coats of special paint for steel bridges for all superstructure steel.
- Replacement of 10 expansion joints of the motorway with new rubber ones.

In 2017, the rehabilitation works was carried out by China Heilong Jiang Roads and Bridge Construction Company and it were completed and the Bridge was reopened to traffic in April 2018. The rehabilitation has increased the capacity of the bridge to a total of 61,000 vehicles per day by accommodating an additional 27,000 vehicles per day and have increased its design life to a 50

effect of fatigue maybe achieved, for example, by reducing the amount of load and loading cycles, increasing cross sectional area of the member, reducing the load on the member by redistributing the load by adding additional members.

Research Centre of the European Commission (the JRC) and the European Convention for Structural Steelwork (ECCS) (B. Kühnet al., 2008) published jointly a European recommendation as a JRC scientific and technical report, regarded as part of the Euro code background documents.

The recommendations give the general procedure for the assessment of existing structures [7]. The procedure uses the safe life method in accordance with nominal stresses. The

Fig. 4: Blue Nile Steel Bridge Elevation Cross-sections.

extra years.

B. Fatigue Assessment

Fatigue develops a crack through a two stages process including crack initiation and crack propagation as seen in Fig. (5), in order to evaluate and asses the fatigue remaining life there are two approaches which are classical (S-N curve) plotted with the cyclic stress (S) against the cycles to failure (N) on a logarithmic scale. and fracture mechanics[5].

Fig. 5: Stages of Fatigue Crack (H. Mughrabi, 2015)[6].

Older structures require special consideration with regard to fatigue since often it was not taken into account in design. Avoiding or reducing the

assessment is divided into four levels: preliminary, detailed, expert and remedial.

If a bridge passes the general assessment procedure for immediate resistance (design or service), then a fatigue endurance procedure is carried out. This procedure is usually decisive in calculating the remaining residual service usability of a bridge. Moreover, the full fatigue assessment procedure advised by the JRC recommendations is followed [7],[8]. According to AASHTO, the remaining safe life is given by:

$$Y_f = \frac{fK \times 10^6}{TaC(RsSr)^5} - a \dots \dots \dots \text{Eq. (2.1)} \quad [9]$$

where;

f Remaining life factor.

K Constant for detail category as per AASHTO.

Ta Daily truck traffic in shoulder lane.

C Cycles per truck passage.

Sr Nominal stress range produced by truck load in ksi.

Rs Reliability factor.

a Age of bridge in years.

C. Previous investigations on fatigue

In an investigation reported including more than 100 fatigue damage cases on fatigue performance of existing steel bridges [10]. The damage cases were categorized according to the type of detail and/or the mechanism behind the observed fatigue cracking. It was found that more than 90% of all reported damage cases are of deformation-induced type. According to Fig. (6). The most common type deformation-induced fatigue damage can be found in the connections between stringers and floor beams, between the latter and the main load-carrying elements in the bridge and the connections of diaphragms and cross-bracings [10].

The classification of a fatigue prone member is determined by factors such as:

- Detailed geometry of the joint.
- Stress range level.
- Number of stress cycles.
- Loading history.

Fig. 6: Collected fatigue damage cases listed according to the type of detail in which they were encountered [10].

D. Previous investigations and Assessments of Blue Nile Bridge

In 1981, an American group led by Prof. J. W. Fisher carried out a third investigation of the four steel bridges[11]. The study revealed that the stringers in the railway were the most critically stressed component of the bridge, this was attributed to the fact that under continuous loading cycles the stringers have exceeded the crack growth threshold and fatigue limit. Thus, the study has concluded that detectable fatigue cracking has already occurred in one or more of the riveted stringer component and that the stringers should be replaced to prevent further fatigue damage , though the crack is yet to be visible [11].

In June 1994, an investigation conducted by a Sudanese company called EPAC have recommended that the fatigue effects should be carefully assessed and railway track to be properly maintained thoroughly. The investigation were carried out under supervision of Prof. Dafalla Turabiof the Faculty of Engineering, University of Khartoum[12].

In 2004, a study carried out by a German company called Dornier Consulting GmbH has also concluded that the railway stringers have developed a fatigue crack, they recommended an immediate replacement, despite they failed to determine the location of the crack , hence the crack is not visible [13].

In 2009, an investigation conducted by The China Jilin International Cooperation (JIC) revealed the bridge steel structure in terms of fatigue life meets the demands of infinite life. However, the investigation also revealed that the railway stringers is to be strengthened and maintained [4].

Thus the previous investigations have concluded that the most critical component regarding fatigue resistance are the railway stringers. This was attributed to their shorter influence length compared to other members, for example, a truss member will experience one complete stress cycle as a result of a passing train, whereas the stringer will experience a number of stress cycles as the same as the number of axles in the train (i.e. two for each carriage). This fact simply indicates that these members have, over the years, been subjected to the largest amount of fatigue damage accumulation [14].

3 METHODOLOGY

A. General information and current condition

The Blue Nile Bridge railway track consist of sleepers which are bolted onto the road and rail level bearings on both sides. A ribbed steel slab with two sleeper bolts connecting them to the wooden sleeper serves to connect the rails. In addition to this, there is a derailer device over the entire length of the bridge (two rails)[13]. Also two lines of longitudinal stringers which are connected by rivets to the transverse floor beams are placed to carry the railway track in which as shown in Fig. 7.

Fig. 7: Longitudinal stringers.

The current condition of the railway appears to be highly damaged, which is attributed to impact generated by train traffic movement as well as a repetitive load cycles over the past 112 years. As a result, the stringers of the railway are overstressed, and many sleepers are leaned and rails are misaligned as reported in the EPAC's Investigation[12]. Most of them had been corroded as shown in Fig. 8 (a) and (b).

Fig. 8: (a) Leaned sleepers, (b) Corroded sleepers

The misalignment of the rails causes inward and outward movement of the train carriages, therefore causing the effect of loading and unloading simultaneously. Thus, it's responsible for inducing secondary stresses in the stringers in which it is considered one of the reasons of stringers being overstressed, the fasteners fixing the sleeper and railway had been severely damaged as a greater number of bolts are lost, there are 906 damages found in sleeper, 324 pieces of fastener damaged, and 3079 bolts lost [4].

B. Modeling

B. 1. Assumptions considered

Modeling of the bridge was carried out using MidasCivil 2006 v7.01, Finite Element model were generated by using Midas FEA 2016 v1.1, Midas Information Technology Co. Ltd, Seoul. The following assumptions were made for the purpose of running the analysis through FEM: -

- The riveted connections are assumed to be fully-fixed. Previous investigations have

revealed that full connection fixity results in mid-span bending stresses at the stringers and cross-girders with an accompanying increase in the bending stresses near the connections [14],[15]. Furthermore, in these studies, the results obtained under the assumption of full connection fixity were found to be in better agreement with field measurements than the ones obtained under a pinned connections assumption [15].

- The trains are traversed in static steps of 1 m over one track of the bridge. The axle loads are applied directly on the top flanges of the stringers thus neglecting any load spread due to the rails and sleepers. This assumption has been found to result in higher stresses [16],[17].
 - For a longitudinal stringer, as such as in this case study, it's assumed that potential fatigue damage has accumulated in the mid-span lower tension flange, as shown in Fig. 7 [18].
- Therefore, as boundary conditions the following were assumed:
- Bridge supports were assumed to be hinged to simplify the analysis.
 - Stringer riveted connections were assumed to be fully fixed.

B. 2. Loading Type and classification:

According to Jilin's report [4], the steel grade is equivalent to that of St 37 of Germany code in which it is also equivalent to A36 of ASTM [4].

- Modulus of Elasticity (Young's Modulus) $E = 200 \text{ GPa}$.
- Tensile Strength = 510 MPa.
- Train Traffic:
 - Maximum velocity: 40 km /hr.
 - Train loads (two locomotives were assumed) :1980 kN (990 kN for each train carriage) = 33 kN/m
- Vehicle loading for fatigue evaluation. The following Loading data was adopted:
 - Group 1: HS 20-44.
 - Group 2: HL-93TRK (Heavy Truck) as design Truck and design lane load are both considered.
 - Train loading.
 - Lane loading (from AASHTO LRFD).

Fig. 9: Blue Nile Bridge Model by Midas Civil 2006.

Fig. 10: Blue Nile Bridge Mesh by Midas FEA.

- Impact loading: According to AASHTO LRFD

- I (Impact friction) = $\frac{50}{L+150}$ (where L : Bridge span loaded to create maximum stress , ft)
 $L = 66.6 \text{ m (218.5 ft)}$, $I = 0.136$
 $(13.6\% < 30\% \dots \text{OK})$
- Bridge deck load (including the Sidewalk) = 55 kN/m [4].
- Structural density for all truss members is 76.98 kN/m^3 .

B. 3. History of traffic loading cycles

According to Deborah J Marcotte [11], Table I illustrates train traffic history for the bridge, the following was assumed (approx. estimation):

- The period between 2000 and 2018, the number of trains were assumed the same as in year 2000.
- For passenger trains, the new train for Khartoum – Atbara Line were added by the assumption of 2 trips /day in the period from 2014-2018.
- Unit trains means small passenger trains with three of four passenger cars.
- Number of Trains from 1906 up to year 2018 (cumulative) = 299,040 freight cars + 93,088 passenger trains + 18,096 unit trains (small passenger trains with three or four units) = 410,224 trains.

- No of stress cycles = $410,224 \times 4 = 1.640896 \times 10^6$ (assuming two carriages per train where one carriage develops two cycles as mentioned previously).

The Fig. 11 illustrates the estimated train traffic on the Blue Nile Bridge according to Deborah J Marcotte [11].

Fig. 11: Estimated Train Traffic on the Blue Nile Bridge according to Deborah J Marcotte.

TABLE I: NUMBER OF TRAINS PER YEAR ESTIMATED FROM TERTIARY SOURCES.

Year	Freight Trains	Passenger Trains	Unit Trains
1909	1440	648	0
1935	1440	648	0
1960	1440	648	0
1981	5280	1176	312
2000 (Low)	5280	1176	312

4 ANALYSIS

A. Fatigue Remaining Life

The remaining fatigue life evaluation is usually considered in case of the crack is not visible when it should. Classical approach was adopted for assessment of remaining fatigue life of Blue Nile Bridge, the classical approach depends on Palmgren–Miner rule [15], the damage accumulation law which is expressed as,

$$D = \sum_{i=1}^n \left(\frac{n_i}{N_i} \right) \dots \dots \dots \text{Eq. (4.1)}$$

It says that a load cycle with amplitude S_i adds to the cumulative damage D , a quantity $\left(\frac{1}{N_i} \right)$. Here, N_i denotes the fatigue life under constant amplitude loading with amplitude S_i and n_i is the number of load cycles at this amplitude. This rule is independent of sequence and fatigue failure is expected when these fractions sum to unity (i.e. $D_n=1$). for fatigue analysis for the (stress-life) method using the S-N curve was applied, this is because the Blue Nile Bridge fatigue condition is particularly in the high-cycle

fatigue (HCF) regime (approximately larger than 10,000 cycles), which in this case the stress life method is suitable [19].

The S-N curve is a line graph, which shows the relationship of the stress amplitude (S_a) and the cycle to failure (N_f) as shown in Fig. 12. S_a is caused by a reverse loading of constant amplitude.

Fig. 12: S-N Curve (alternating stress amplitude (S_a) versus number of cycles (N_f) to failure).

For fatigue analysis, static analysis is performed first. Then the stress amplitude is found by selecting one component among the maximum absolute stress, minimum absolute stress and Von Mises stress. Applying this to the S-N curve, we can find the number of cycles of the repeated load at which fatigue failure takes place.

B. Loading cases

Loading cases are in accordance with AASHTO LRFD, the following loading cases and boundary conditions were applied as shown in Fig. 13:

- Loading Case No.1 – Strength-I: 1.25 D.L (DC) + 1.75 L.L (M) as (M) represents moving load.
- Loading Case No.2 – Service II: 1.0 D.L (DC) + 1.30 L.L (M).
- Loading Case No.3 – Strength-IV: 1.50 D.L (DC).
- Loading Case No 4 – Fatigue: 0.75 L.L (M).

Where the dead load is (deck + Sidewalk + railway section) self-weight and the live load is (Vehicle + Train loading).

5 RESULTS AND DISCUSSION

A. Analysis and Calculation Output

By using Midas civil 2006, the maximum and minimum stress values for loading case are determined as shown in Table II. The maximum and minimum stresses for the stringers in the loading case: fatigue, are 492.918 and 358.49 MPa respectively as illustrated in Fig. 14.

Fig. 13: Loading Cases for the Model of Blue Nile Bridge.

TABLE II: MAXIMUM AND MINIMUM STRESSES FOR DIFFERENT LOADING CASES - STRINGER.

Loading case	Member	Maximum stress (MPa)	Minimum stress (MPa)	Location
LC 1	Stringer	1744.71	1506.17	Mid-span of all spans
LC 2	Stringer	1330.68	1145.7	Mid-span of all spans
LC 3	Stringer	671.492	454.919	Mid-span of all spans
Fatigue	Stringer	492.918	358.49	Mid-span of all spans

Using the (stress-life) method using the S-N curve, cycles to failures are determined to be $N_f = 9.5513E+05$ cycles as shown in Fig. 15.

The total damage accumulation was calculated by applying damage accumulation law of Palmgren–Miner rule [20]:

$$D = \sum_{i=1}^n \left(\frac{n_i}{N_f} \right) = \frac{1,196,1}{955,1} + \frac{372,3}{955,1} + \frac{72,3}{955,1} = 1.25 + 0.39 + 0.08 = 1.72$$

Where number of stress cycles generated by train traffic from freight cars, passenger trains and unit passengers as the first term, second term and third term of abovementioned equation respectively.

B. Discussion of Results

The main purpose of this paper is to present a fatigue assessment of the Blue Nile Bridge, in order to decide on both the type and urgency of the appropriate course of action regarding the most critical member (Fatigue prone), which in this case are the railway stringers.

Fig. 14: Maximum and Minimum Stresses for Loading case : Fatigue.

Fig. 7: Meshed Geometry of Railway Section of the Bridge by using quadrilateral triangular elements.

Fig. 6: S-N curve for Alternative Stress Amplitude S_a vs Number of Cycles to failure N_f .

The use of FEM concept is to find a more accurate solution is applied by the model mesh generation, in which Using 1D linear elements results in a rigid model with less accuracy, whereas using quadrilateral triangular elements increases the accuracy and lessens the rigidity of the geometry, a meshed geometry of the railway section is shown in Fig. 16.

The results indicate that the stringers have experienced stress cycles exceeds the number of cycles to fail (number of experienced stress cycles due to train from 1906 to 2018) is $N=1.640896 \times 10^6$, Thus the number of stress cycles to fail is $(N_f) = 9.5513 \times 10^5$ which implies that a fatigue crack has already been initiated either in the mid span lower tension flange of the stringer or at the corner of the L-profile of the stringer, with the latter is less probable to occur given the results. When the fatigue failure obtained from the S-N curve occurs at a high numbers of cycles ($N > 10^6$ cycles), the cycle is considered a high cycle fatigue (HCF), in which is similar to this case study. The problem lies with the invisibility of the fatigue crack to the naked eye, which probably is a macro crack; a sub-microscopic crack [21].

However, in this case the JRC gives recommendations to initiate phase 3 study since the total damage accumulation comes out to be greater than one ($D > 1$) [7]. To increase fatigue resistance of the stringers the use of strengthening technique is carried out by adding steel plates to the bottom flange of the stringer by welding [22], this technique has proved to be more feasible and practical where time and cost are reduced to a minimum due to simplicity of the design and it requires little special equipment and minimal labour [22].

Start of the fatigue crack initiation is on year 1993 as predicated according to the diagram shown in Fig. 19 which is based on the bridge's load history records mentioned by Deborah J Marcotte [11]. However, this predication is not entirely accurate due to the following causes:

- The non-linearity of the diagram's curve from the period year 1960 and inwards, which is attributed to the extensions of the railway to SENNAR - ROSERIES, and BABANOSA and NEYALLA, therefore resulting in a sudden increase in the train traffic.
- Complexity of the fatigue crack mechanism throughout its phases (crack initiation, crack propagation).

Therefore, it is practical to assume that the fatigue crack has developed at some point of time in the period between year 1981 and year 2000.

Fig. 8: Annual train stress cycles.

6 CONCLUSIONS AND RECOMMENDATIONS

Previous studies and investigations carried out on the Blue Nile Bridge have concluded the necessity for a full fatigue assessment for the railway stringers as the most critical member. Some of these studies have recommended strengthening or replacing the stringers.

The current conditions of the railway stringers are critical due to the stringers being overstressed, this is attributed to impact generated by train traffic as well as a repetitive load cycles over the past 112 years. The maximum stresses were found at mid span under full connection fixity thus confirming the previously related assumption.

- Finite element modeling coupled with field measurement data gives a good approximation solution. The use of Midas Civil 2006 V.7.01, Midas FEA 2016 V1.1 simultaneously, and FEM model calibrated by the field measurements data from the past studies and investigations of the Blue Nile Bridge gave initially accepted values. However, due to the limited field measurement data regarding fatigue analysis, comparison of the constant amplitude stresses between FEM model and field measurement data was not made.
- No of experienced stress cycles due to train traffic over the years from 1909 to present exceeds the number of stress cycles to failure, the period from 1981 to 2000 were identified as the time zone for which the fatigue crack has presumably developed. The recommendations can be as follow:
- It is recommended to initiate phase 3 of the fatigue assessment as per The JRC recommendation (site visit, discussions, analysis using fracture mechanics and/or probabilistic method). Fracture mechanics analysis is required to determine the fatigue crack growth rate since the fatigue crack is sub-microscopic and not visible to the naked eye (macro-crack).
- It is recommended to use the technique of strengthening the stringer by adding material such as steel plates to the bottom flange of the stringer.
- It is recommended to procure and install Structural Health Monitoring System (SHMS)

for detection of fatigue cracks, the cost of installing SHMS (hardware and software) is ranged between 50,000 to 100,000 USD [23], considering both the importance of the Blue Nile Bridge and the consequence of failure. The cost of obtaining SHMS is regarded as an economical, practical and safe choice. As one could refer to the failure of Genoa's Morandi Cable Stayed Bridge in Italy on August 2018. This failure could have been mitigated by the use of SHMS.

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