The Miller Park Crane Collapse –
Analysis of the King Pin Failure

Engineering Systems, Inc.
3851 Exchange Ave.
Aurora, IL 60504
(630) 851-4566

Abstract: While lifting a one million pound section of space frame roof structure at the Miller Park construction site, a crane failed and overturned, resulting in three fatalities and extensive damage to the stadium. During the ensuing failure investigation, the strength of the crane’s king pin, a 12” diameter, 11’ long steel shaft about which the front crawler body rotates, was a key issue along with any changes in king pin strength that may occur with various king pin connection details. ABAQUS/Standard was used to investigate these questions with a quarter symmetry solid element model of the king pin and its associated connection details. The model included multiple 3D deformable body-to-deformable body contact surfaces and material nonlinearities. The analysis showed the variation of king pin strength with differing king pin connection details and this information was used as part of the multi-disciplinary investigation to determine a probable cause for the failure of the crane.

Keywords: Failure Analysis, Contact, Plasticity

1. Introduction

The construction of Miller Park, a retractable roof baseball stadium, required the use of a highly specialized, heavy-lift crane. The crane was used to lift, move and position large sections of the space frame roof structure. While lifting a one million pound section of space frame, the heavy-lift crane failed and overturned, resulting in three fatalities and extensive damage to the stadium. Engineering Systems, Inc. (ESI) worked as part of a multidisciplinary team to investigate the cause of the heavy-lift crane collapse. Issues addressed during the investigation of the collapse included material, structural, aerodynamic, geotechnical and dynamic issues, among others. This paper focuses on the finite element analysis study of the crane’s king pin in ABAQUS/Standard, which was used to assist in the king pin failure analysis as well as the development of a full crane finite element model which was also used during the investigation.
2. Background

The heavy-lift crane used at the Miller Park construction site had a somewhat unique configuration, consisting of two separate crawlers 100 ft. apart and connected by a space frame structure called a stinger (see Figure 1). The boom and mast connected to the front crawler tub, which rested and rotated on a 14 ft. diameter slide bearing. The rear crawler carried $2.4 \times 10^6$ lbs. of counterweights to resist the forward over-turning moment of the lifted load. In order to translate a load, the front and rear crawlers, each with a separate operator, were moved in unison. When swinging the boom, the front crawler remained stationary and the rear crawler moved about it. The height of the load was controlled by a third operator stationed on the stinger. At the time of the collapse, the jib tip was roughly 530 ft. above the ground.

![Figure 1. Heavy-lift crane configuration.](image)

The front crawler tub rotated on the front crawler using the king pin as a pivot. The king pin is a 12 in. diameter, 11 ft. long, solid shaft made of 4340 steel with a yield strength of 103,000 psi. In normal service, the king pin does not see any upward loading and acts purely as a pivot. If the crane is subjected to excessive side loading, the king pin can be exposed to upward loading due to tipping of the front crawler tub. When this occurs, the king pin and its connections must resist an axial, tensile load.
The original design of the king pin connection had a large nut at both the top and bottom of the king pin, both of which threaded onto the king pin as shown for the top connection in Figure 2. The lower connection was later changed to include a roughly 2 in. thick split ring which engaged a recess in the king pin and was locked in place by a three quarter inch thick locking ring. Both the split ring and locking ring were made of A514 steel with a 100,000 psi yield strength. During the collapse investigation, the as-built lower connection detail was found to vary from that specified in the drawings (as-drawn), mainly by the addition of a half inch thick spacer made of CDA 932 bronze with a yield strength of approximately 19,000 psi. Another notable difference between the as-built connection and the as-drawn connection was a change in thrust bearing material from the as-drawn CDA 836 brass (17,000 psi yield strength) to as-built CDA 863 bronze (68,000 psi yield strength).

Figure 2. King pin connection details.

On the day of the collapse, the heavy-lift crane was lifting and positioning a section of the roof which was roughly 100 ft. by 200 ft. in size (Figure 3). The section of roof was estimated to weigh over 900,000 lbs and, with rigging and balance weights, totaled 1x10^6 lbs. At the time of the collapse, the load was approximately 250 ft. in the air. The crane, counterweights and lifted load totaled over 6.2x10^6 lbs. A view of the crane and stadium after the collapse is shown in Figure 4.
Figure 3. Heavy-lift crane with load.

Figure 4. Overview of the collapse.
Examination of the lower king pin connection after the collapse showed that the end of the king pin was sheared off below the split ring recess (Figure 5). This allowed the front crawler tub to separate from the front crawler and was the initiating event in the collapse sequence of the heavy-lift crane. As a result, the strength and stiffness of the lower king pin connection became one of the main focuses of the investigation and was studied using ABAQUS/Standard.

![Figure 5. Lower king pin failure.](image)

3. Analysis

Two three-dimensional, solid element, ABAQUS/Standard finite element models were built in order to analyze the as-drawn and as-built king pin configurations (see Figures 6 and 7). Each model focused on the components at the lower connection of the king pin and front crawler, and included only the lower 30” of the king pin. The locking ring and split ring were tied together in the area of the retaining bolts. All other surfaces in the models which may have contacted each other were modeled with 3D-to-3D deformable body contact, resulting in 13 separate contact surfaces in the as-built model. Because the nature of the geometry dictates that the lower king pin connection is loaded axially, each model could take advantage of quarter symmetry to reduce the overall degrees of freedom.

Of course, the overall strength of the lower king pin connection was of great interest to the investigation. Equally important, though, was the stiffness of the king pin and its lower connection. This is because once the king pin is loaded in tension, any deformation results in additional displacement of the jib tip, which increases the load on the king pin (the so-called P-δ effect). Because the analysis was developing a load versus deflection curve for the lower connection, the top of the king pin was loaded via displacement control, which is much more stable during a contact simulation.
All components were assigned elastic/plastic material properties in order to account for material yielding which occurred in each component prior to any individual failure within the connection detail. Generic material curves were used for all components except the king pin, which was sectioned and subjected to tensile testing as part of the investigation. The behavior of the connection varied with friction between the components and numerous friction values were analyzed during the investigation process. This paper focuses on the analyses with a lubricated friction value of $\mu=0.1$.

The models were analyzed using ABAQUS/Standard version 5.8 run on a PC (circa 1999). Run times were as long as 24 hours, covering two steps and roughly 20 total increments. The models were run again with ABAQUS/Standard version 6.5 on a PC (circa 2006) with run times of roughly an hour.

### 3.1 As-drawn king pin model

The as-drawn king pin model is shown in Figure 6 and is comprised of the following components:

- CDA 836 leaded red brass bushing/thrust washer
- ASTM A514 steel split retainer
- ASTM A514 steel locking ring
- AISI 4340 steel king pin
- A572 steel front crawler body.

The model consists of 7983 C3D8R and C3D6 solid elements and 10435 nodes. 3D-to-3D deformable body contact was defined between components as required and tied contact was defined on the king pin and crawler for purposes of mesh refinement. The model has 37638 degrees of freedom.

### 3.2 As-built king pin model

The as-built king pin model is shown in Figure 7 and is comprised of the following components:

- CDA 863 manganese bronze bushing/thrust washer
- ASTM A514 steel split retainer
- ASTM A514 steel locking ring
- AISI 4340 steel king pin
- CDA 932 high leaded tin bronze spacer
- A572 steel front crawler body.
The model consists of 8445 C3D8, C3D8R and C3D6 solid elements and 11171 nodes. 3D-to-3D deformable body contact was defined between components as required and tied contact was defined on the king pin and crawler for purposes of mesh refinement. The model has 40674 degrees of freedom.

Figure 6. As-drawn king pin model.

Figure 7. As-built king pin model.
4. Results and Discussion

4.1 Load versus deflection curves

Load versus deflection curves for the as-drawn, as-built and nut connection are shown in Figure 8. The curve for the nut connection is based on hand calculations, while the as-drawn and as-built curves represent the finite element analysis results. It is clear that the nut connection is appreciably stiffer and stronger than either connection with a split ring detail. Under normal service this is of no consequence, as the king pin is not loaded in tension and the strength and stiffness of the lower king pin connection is not germane. Once the king pin is loaded, an unusual and critical condition in and of itself, the split ring design detail is significantly less robust and will, because of its relative compliance, further amplify the load on the king pin even before any failure occurs within the connection.

![Figure 8. Load versus deflection curves for the king pin models.](image)

The results shown in Figure 8 were used as the basis for a non-linear spring element in a full crane model used to investigate the P-δ effect on the crane under side loadings large enough to load the king pin in tension. This analysis is discussed in a companion paper presented elsewhere in the 2006 ABAQUS Users’ Conference (Wilkinson, 2006).
4.2 As-drawn king pin model stress results

Figure 9 shows a von Mises contour plot of the as-drawn lower king pin connection under a 2300 kip load. This plot clearly shows that the highest stresses in the king pin and split retainer occur 90 degrees away from the split in the split ring. At this load, yielding of the king pin and split ring has occurred, although yielding at the corner of the king pin lower land is very localized.

![Figure 9. As-drawn king pin at 2300 kip load [psi].](image)

A von Mises contour of the thrust bearing in the as-drawn lower king pin connection under a 2300 kip load is shown in Figure 10. There is significant yielding in the thrust bearing under this load and the thrust bearing is near failure. The highest stresses in the thrust bearing occur at the split in the split ring.
4.3 As-built king pin model stress results

The von Mises stress state of the as-built lower king pin connection under a 2400 kip load is shown in Figure 11. As with the as-designed lower king pin connection, yielding of the king pin and split ring has occurred at this load level and is most severe 90 degrees from the split in the split ring.
Figure 12 depicts the spacer of the as-built lower king pin connection under the same loading. The spacer exhibits significant yielding and is at the ultimate stress of the material adjacent the split in the split ring. The analysis shows that the split ring rotates upward under load and works to extrude the spacer from the lower king pin connection stack-up. The split ring at its split basically cuts into the spacer as would a shear, making the loading at this point of the spacer most severe. As the spacer is extruded, the analysis shows the original rectangular cross-section is tapered under the severe loading. This predicted deformation of the spacer correlates well with the physical evidence, as shown in Figure 13.

![Figure 12. As-built spacer at 2400 kip load [psi].](image)

Figure 12. As-built spacer at 2400 kip load [psi].

![Figure 13. Post-accident cross section of the as-built spacer.](image)

Figure 13. Post-accident cross section of the as-built spacer.

4.4 Failure analysis

The overall investigation showed that sufficient side loads were developed due to wind loads, soil settlement, P-δ and dynamic effects to load the king pin significantly, but not
enough to shear the end of the king pin (which requires a load of approximately 6700 kip). Figure 8 shows the strength of the as-drawn and as-built lower king pin connections before first failure are similar, on the order of 2400 kip. At this load, which is achievable under the conditions of the lift, the spacer in the as-built connection will fail.

Physical evidence shows that, upon failure, the spacer was ejected from the lower connection stack-up, moving the jib tip further to the side. This dynamically increased the load on the lower king pin connection and failed the thrust bearing (which, as can be deduced from the as-drawn analysis, is loaded by the split ring similarly to the spacer). The thrust bearing failure results in further movement of the jib tip and a further increase in the king pin load. At this point, enough load can be developed to fail the end of the king pin in shear and the front crawler tub is free to overturn resulting in collapse of the heavy-lift crane. This step-by-step failure of the lower king pin connection, as predicted by the finite element analysis, is supported by the physical evidence and a video (w/ sound) of the collapse.

5. Conclusions

- The lower king pin connection of a heavy-lift crane involved in a construction site accident was modeled using ABAQUS/Standard as part of a multidisciplinary failure investigation into the crane’s collapse.

- The finite element analysis study provided a stiffness curve for the lower king pin connection which was used in the development of a full crane model. The strength of the as-drawn lower king pin connection at first failure was found to be about 2300 kip. The strength of the as-built lower king pin connection at first failure was found to be about 2400 kip.

- The failure investigation showed that loads at the time of the accident were enough to exceed the strength of the spacer in the lower king pin connection as predicted by the finite element analysis. The finite element analysis also provided insight into the subsequent failures of the lower king pin connection which eventually lead to the collapse of the heavy-lift crane.

- The finite element analysis technique is a powerful and effective failure analysis tool.

6. References
