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Damage assessment and preservation of suspending system of Yongle-Big-Bell

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ABSTRACT: The Yongle-Big-Bell is an exquisite heritage of ancient China and has more than 600 years history. The long history renders the suspending wooden rack serious damage. Therefore, the security is of our great concern. In order to know if the wooden rack is safe or not for the conventional striking in the festival service, a systemic research work has been done. At first the existing deformation and response to the strike of the beetle were measured, and then calculations using method of material mechanics and finite element analysis were conducted. Based on the results of our research, some concluding remarks and suggestion were given: The Yongle-Big-Bell can be struck regularly without urgent danger of collapse. In view of the existence of serious rotten damage, the repair and protection of wooden rack are pressing.

1 INTRODUCTION

The protection of historical cultural buildings is a pressing task of modern science and technology in the whole world. China is a country of 5000 years civilization and abounds with many cultural heritages. A vast amount of ancient constructions needs to be repair and maintenance. The theme of the present conference meets our interests in this area.

The Yongle-Big-Bell is a well known historical relic of China, which was cast from bronze in the Ming dynasty i.e. 600 years ago (Big-Bell Temple Ancient Bell Museum, 1998). The long history renders the suspending wooden rack serious damages, with one of the largest rotten holes in 30 cm deep. In this circumstance, the safety and reliability are of our great concern. In order to verify whether the bell and its wooden rack are safe or not for the conventional striking in the festival service or when earth-quake happens, some measurements and calculations were carried out. In the present article, the results are presented and discussed.

Four aspects of the research have been done:

(i) The inclination of the wooden rack and the tilt of the main beam were measured. By using the professional instruments for construction, the slant angle of the pillars at four corners and the tilt of the main beams were measured.
(ii) The dynamic response of the wooden rack to the stroke on the bell by the conventional beetle was tested and analyzed. The in-put curves of the stroke, i.e. the acceleration versus time curve and the force versus time curve were measured by the sensors installed on the beetle. And the response curve i.e. acceleration versus time curve was recorded by the sensors installed on the top of the main beam.
(iii) Strength analyses of the dangerous parts of the suspending and bearing systems were conducted. The stresses and deformation of beams of No.1 and No.4 and those of the metallic bolt for connecting the Big Bell and the beam were calculated.
(iv) The FEM analysis of the Bell and the suspending system as a whole was performed.

Finally, according to the results obtained, the following concluding remarks were drawn. The Big Bell can be struck regularly without urgent danger of collapsed, and on the New Year eve it can be struck as usual. It is not necessary to suspend this service. In view of the existence of quite serious rotten voids in the beams say No.4, repair and protection of wooden rack are pressing. Some suggestions on strengthening of the damaged beam and detection of deformation of wooden rack as a routine job in future were proposed (Zhang, et al, 2005).

2 GENERAL DESCRIPTION ON THE YONGLE-BIG-BELL

2.1 *Background of the research*

According the written history, the history of Beijing can be dated back to the Warring States Period (around 10th century BC). Beijing has been the capital of 5 dynasties: Liao, Jin, Yuan, Ming and Qing. The emperor Chengzu (named Zhudi) of Ming Dynasty initiated and completed three magnificent projects: that is, Forbidden City, Temple of Heaven and the Yongle-Big-Bell. The Big-Bell weighs 46 tons with 3.3 meters in rim diameter and 6.75 meters in height. It is suspended on a wooden rack composed of 10 beams and 8 pillars. More than 230,000 characters of Han and Sanskrit sutra and incantations are cast on the

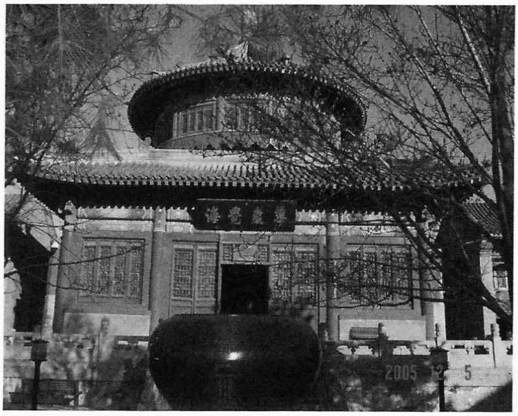

Figure 1. Photograph of the building for Big-Bell.

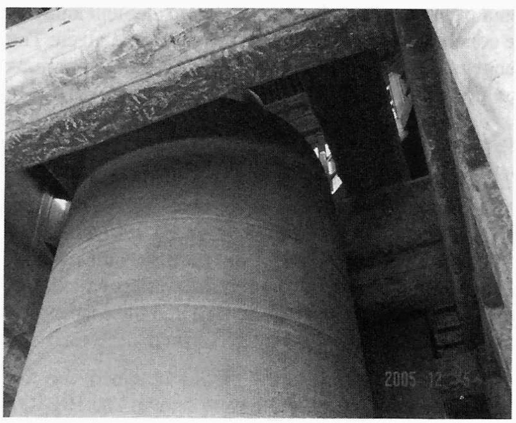

Figure 2. Photograph showing the Big-Bell hanging on the wooden rack.

Bell. The casting technology is exquisite and illustrates wisdom of laboring people in ancient China.

Owing to the existence of obvious rotten caves in the beams of wooden rack, the authorities in charge of the Museum of Yongle-Big-Bell worried about the security in the service of the Bell. So we were invited to make the assessment on the reliability of the Bell and particular of the wooden rack.

2.2 *Yongle-Big-Bell*

Figure 1 shows the building in which the bell is housed. It is the main construction in the Sheng-Jue Temple (also named Big-Bell Temple) which is located in the northwestern part of Beijing.

Figures 2 and 3 show the photographs of the upper part and the lower part of the Big-Bell respectively. Figure 4 is the photograph showing the inscribed characters of Chinese and Sanskrit sutra, which are clearly cast and no single letter is mistaken. That illustrates the high level of metallurgical technology of ancient China 600 years ago.

Figure 5 is a downward view photograph illustrating the detail of the connection between the main beam of

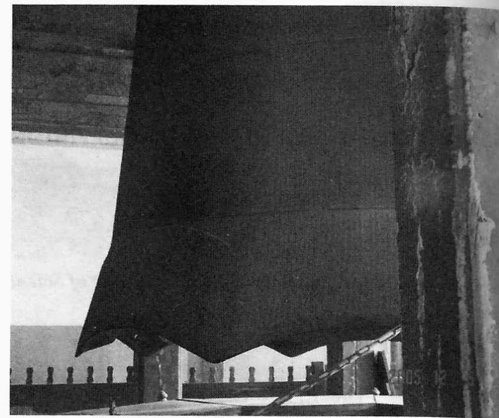

Figure 3. Photograph showing the lower part of the Bell.

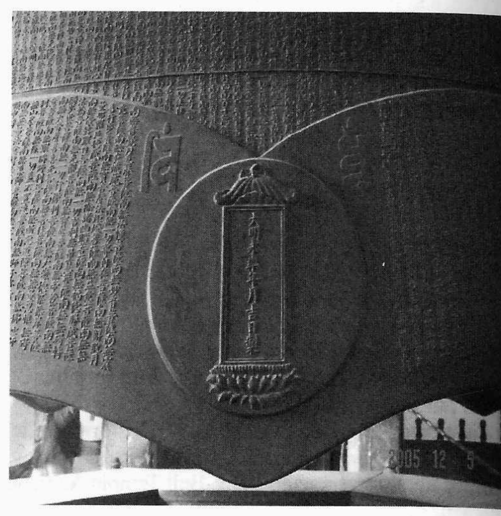

Figure 4. Photograph showing the characters inscribed on the Big-Bell.

Figure 5. Photograph showing the detail of the Bell hung on the main beam through the steel hook (downward view).

the wooden rack and the steel ring, which links the ring-shaped upper-handle of the bell through a bronze bolt. Figure 6 shows the upward view from the ground of the connection of the bell to the main beam. Because

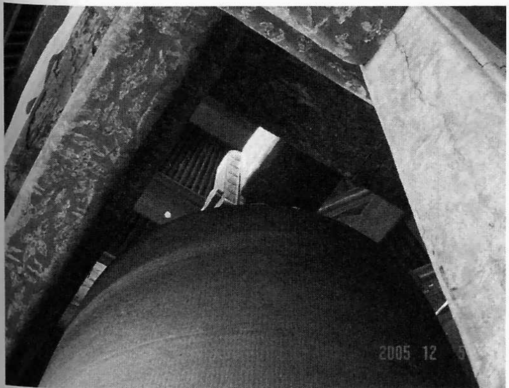

Figure 6. Photograph showing the detail of the Bell hung on the main beam through the steel hook (upward view).

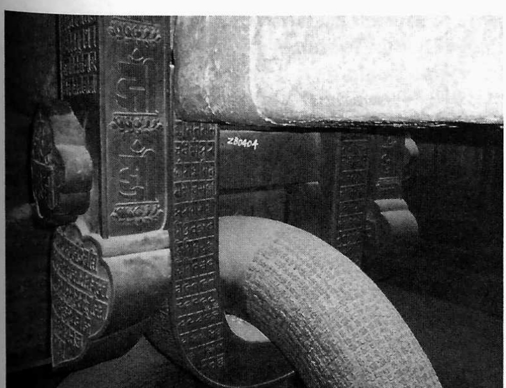

Figure 7. Picture showing the detail of connection of the handle of the bell to the main beam through the hook and bronze bolt.

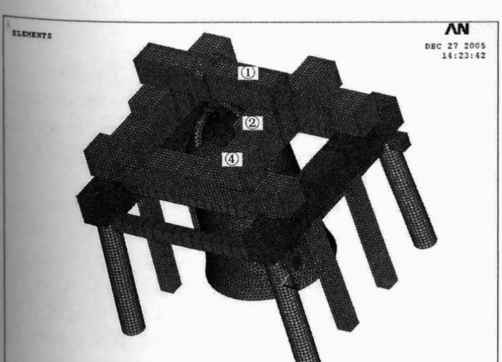

Figure 8. Schematic drawing of the bell and the suspending wooden rack.

the space of the building is quite narrow, we could not take a whole picture of the Big-Bell, the supporting wooden rack and the connecting system through the hook and the bolt in a whole prospect.

From Figure 7 we can see clearly the detail of the connection of the Big-Bell to the wooden rack. It seems that the bolt is quite slim and is one of our main concerns for the reliability of the big-bell.

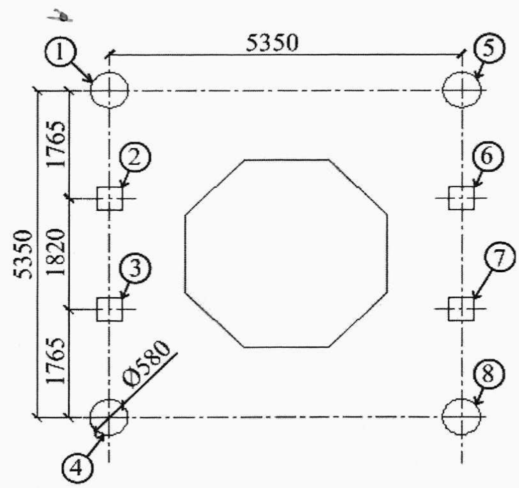

Figure 9. Positions of the 8 pillars.

Figure 8 is a schematic drawing of the whole system including the bell and the suspending wooden rack, which is composed of 8 pillars and 7 beams.

In the following, our main researches on the assessment of the reliability of the structure will be described.

3 RESEARCHES ON THE SECURITY OF THE SUSPENDING SYSTEM

3.1 *Measurement of the existing deformation of the wooden rack*

Several hundred years history incurs some deformations of the wooden rack. Moreover the 1976's Tangshan earthquake gave a severe shock on the Big-Bell. It is no doubt that the bell system has already been subjected a visual deformation. According to the achieve of the Museum of Yongle-Big-Bell, it was suspected that the top of the wooden rack has had transversal displacement of several centimeters. Therefore, the inclination of the wooden rack and the tilt of the main beam should be measured.

3.1.1 *Slant angles of the four pillars*

Slant angles of the four pillars at corners were measured using professional instrument of construction. Figure 9 is the schematic showing the positions of the 8 pillars of the wooden rack. It should be pointed out that in order to have good instability, the 8 pillars all have inward inclination angle. The four corner pillars have inward slant angle of around 3 degrees. The additional deformation angle can be calculated using the following formula:

$$\theta = \arcsin(a / L) \tag{1}$$

where L is the length of pillar, and a is the distance of projection of the top on the ground to the bottom

Table 1. Measurements of slant angles of four corner pillars.

Pillar Number	a (mm)	L(mm)	θ (degree)
1#	239.1	3816.3	3.6
4#	213.7	3815.1	3.3
5#	203.9	3815.6	3.1
8#	202.0	3820.1	3.0

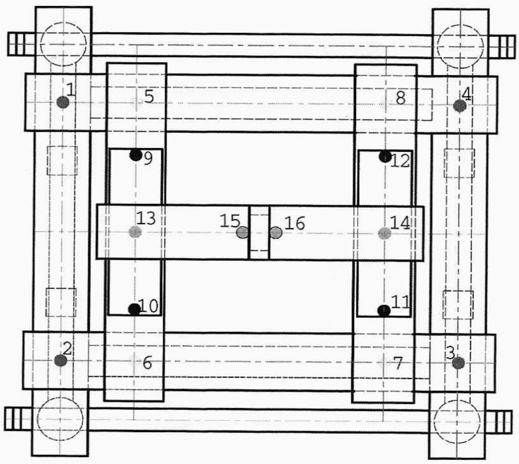

Figure 10. Schematic drawing depicting the measured points.

of pillar. The results are listed in Table 1. The relative difference is within 11%.

3.1.2 *Tilt of the main beam (No.1 beam)*

The number one (No.1) beam bears the whole weight of the bell and its suspending system. We measured the relative height of four points to a standard point, which height is supposed to be fixed. The difference of the measured values gave the tilt of the beam. Figure 10 shows the measured points. In the figure, points 13, 14, 15 and 16 are the measured points on the No.1 beam. It is noted that the east end (right end) is lower than the west (left) end by 33 mm.

The tilt of No.1 beam may be caused by the rotten voids in the beam of No.2 and No.4. No.2 beam is a cushion beam, which lies on No.4 beam and bears the east end of the No.1 beam. The tilt angle can be calculated by the following equation:

$$\alpha = \arcsin(\delta / l) \tag{2}$$

where l is the length of beam and equals to 3 m, δ is the difference of the height of the west end minus that of east end. Simple calculation yields that the tilt angle of the main beam equals about 2 degrees.

From the above measurements, the conclusions were obtained: ① From table 1, we may concluded that the wooden rack does not have undergone obvious deformation, although the slant angles of the four corner pillars have some difference. ② The No.1 beam

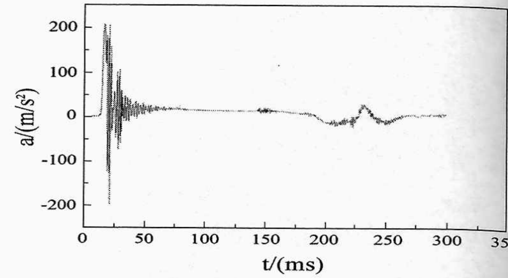

Figure 11. Acceleration versus time curve on the beetle.

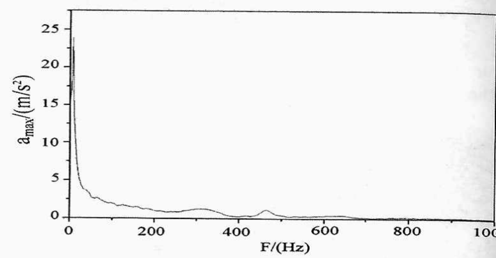

Figure 12. Peak acceleration versus time curve on the beetle.

suffered a little angular displacement due to the rotten damage in the two beams of No.2 and No.4, both of which support the east end of the No.1 beam. ③ It should be mentioned that the No.2 and No.4 beams have obvious rotten damages, whose value can be approximately evaluated using the difference of heights between east end and west end of No.1 beam.

3.2 *The dynamic measurements of the bell and suspending system*

The measurements consist of two parts: The first is to measure the input acceleration (or force) versus time curve on the bell by stroke of beetle, and the second is to measure the response of the main beam (No.1 beam) to the stroke by the beetle.

In order to measure the input force curve of the beetle, a sensor was installed on the top of the beetle. We struck the bell as we do usually. The measured acceleration versus time curve is as shown in Figure 11. The beetle is a wooden trunk of 50 kg in weight. The force versus time curve can be obtained from Figure 11 and has the same shape just as shown in Figure 11, but the ordinate will be changed to unit of force and its value equals to acceleration times the mass of the beetle. The input curve of peak acceleration versus frequency is as shown in Figure 12.

From curve 11, we note that the input maximum acceleration is 207 m/s^2, and using the Newton's Second Law of Motion we obtained force pulse of 1035 kg. According to Figure 12, it should be pointed out that the fundamental frequency of the impact pulse is about 7.5 Hz.

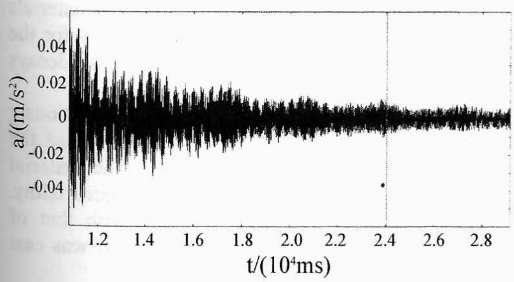

Figure 13. Acceleration versus time curve of the beam.

The response curve of acceleration versus time of the main beam (No.1 beam) was measured simultaneously. The sensor was installed on the top of the beam near to the steel ring on which the bell is hanging. The curve of acceleration versus time is given in Figure 13. The distinguish feature of curve 13 is rapidly diminishing of acceleration with time. Simple analysis yields that the fundamental frequency is 90 Hz and the peak acceleration at beginning period is 0.04 m/s^2. We can also point out that according to the curve of later period the long-term vibration is attributed to the fundamental frequency of the whole system, including the bell, the wooden rack and the connection system. The peak acceleration of 0.04 m/s^2 is not the response of the main beam only, but also includes other components of the whole system, for instance the 8 pillars and other beams. The above reasoning results an important conclusion that response of the No.1 beam itself is much less than 0.04 m/s^2. In ultimate estimation the acceleration of the beam is less than 0.01 m/s^2.

Therefore the maximum impact force on the No.1 beam is much less than its weight of 46 tons.

3.3 *The strength analysis of the suspending system*

In order to know if the key parts of the bell-suspending system are safe or not, the strength of the steel bolt and two main beams were analyzed.

The suspending system is schematically shown in Figure 14 including 8 pillars and 10 beams. Analysis was carried out of strength of the bronze bolt, and No.1 & No.4 beams. The bronze bolt is an important part connecting the upper ring (hook) linking to main beam with the lower ring linking to handle of the bell. Two methods were used, which are method of material mechanics and finite element analysis. The shear stress and bending stress were calculated. For bending, to play safe, the supporting condition was simplified as simple support condition. For finite element analysis we tried several boundary conditions.

The main results are given in Table 2 and Table 3 for material mechanics method and finite element analysis, respectively. It is noted that the bolt is safe with some allowance. As for the two beams No.1 and No.4, they all have large safety factors, since they have large size of cross section.

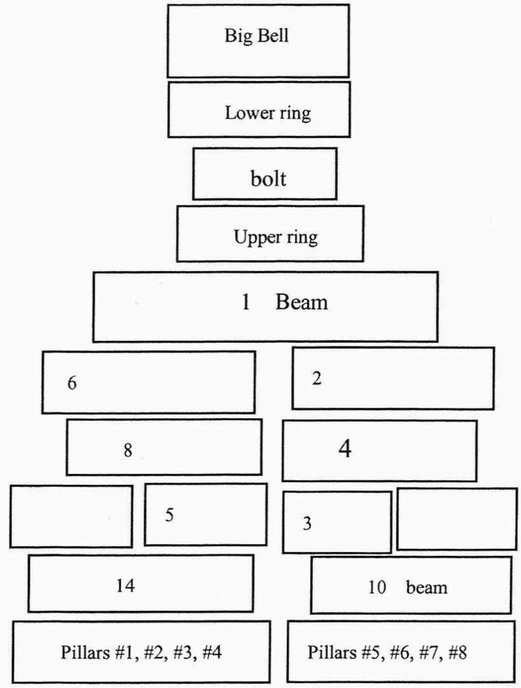

Figure 14. Suspending system.

Table 2. Strength of the bronze bolt (I).

Method of Mechanics of Materials	Shear	Bending
Maximum Stress (MPa)	37.8	164.2
Strength of Material (MPa)	110	220
Safety Factor	2.9	1.3

Table 3. Strength of the bronze bolt (II).

FEM analysis	shear	Maximum Mises Stress*	Bending
Maximum Stress (MPa)	34.7	106	179.
Strength of Material (MPa)	110	220	220
Safety Factor	3.2	2.1	1.2

*The maximum Mises stress happens at the supporting point, whereas the maximum bending stress locates at the middle point of the beam.

3.4 *Finite element analysis of the whole structure*

Strength analysis was carried out using finite element method for the structures of the bell, wooden rack and the suspending system as a whole. Commercial code of finite element method ANSYS 9.0 was used. The element type of Solid 45 is adopted. Only elastic analysis was conducted. The material properties were mainly

Table 4. Maximum normal stress, strength and safety factors of three materials according to maximum normal stress criterion.

$[\sigma_{max}]$ criterion	Stress σ_{max} (MPa)	Strength σ_s (MPa)	Safety factor
Steel	89.5	140	1.56
Bronze	32	120	3.70
Wood	9.5	30	3.16

Table 5. Maximum shear stress, strength and safety factors of three materials according to maximum shear stress criterion.

$[\tau_{max}]$ criterion	Shear stress τ_{max} (MPa)	Strength τ_s (MPa)	Safety factor
Steel	36	70	1.94
Bronze	14.7	60	4.08
Wood	2.35	15	6.38

selected according to material handbook (Mechanical Engineers Society, 1996). It is postulated that for Young's modulus of steel $E_{st} = 200$ GPa and Poisson's ratio $\nu_{st} = 0.28$. For bronze, $E_{bronze} = 100$ GPa, $\nu_{bronze} = 0.34$. The Poisson's ratio of wood is assumed as $\nu_{wood} = 0.28$. The woods are orthotropic materials. Their longitudinal modulus is 5~6 times of its transverse one. The density of steel is $\rho_{st} = 7850\,kg/m^3$, the density of bronze is $\rho_{bronze} = 8200\,kg/m^3$, and the density of woods is assumed as $\rho_w = 500\,kg/m^3$.

The computation is time-consuming. The obtained data are enormous. We pay more attention to the largest stress of the main parts. The main results are summarized in Tables 4 and 5.

The construction of the computation model is a tough and torturing job. A lot of difficulties were confronted. The main difficulties we confronted in the FEM modeling are: (i) The hinge joints between the handle of the bell and the lower metallic ring and that connecting the upper ring and the main beam are hinges with friction, which should be modeled as touch problem. (ii) The roots of the 8 pillars of wooden rack are laid on the ground, this kind of support condition is neither fixed nor simply supported. (iii) The connection between the beam and the pillars is a so-called MAO-SUN structure, which connects the two parts with friction without glue and bolt. And the 10 beams are laid down into three tiers without any connection by glue or bolt. The modeling of these structures is a big difficulty. (iv) The materials constants are of some uncertainty. Especially for the wood, after several hundred years, the wood decays obviously.

The material performance must decline seriously and the real value cannot be obtained, because the destructive tests are prohibited strictly. The material constants of metal materials are also of uncertainty. The data of handbook may not tally with that of the real objects, thinking that the Big-Bell was cast 600 years ago.

4 CONCLUDING REMARKS

Based on the present research the main conclusions are as follows:

(1) The wooden rack has not undergone serious deformation, although it has suffered the Tangshan earth quake in 1976. The bronze bolt and the wooden rack supporting the Big-Bell are safe and there is no danger of break during striking in the festival service.
(2) Owing to the existence of obvious rotten cavities, repair and strengthening are needed. So the following suggestions are proposed.
(3) The main suggestion proposed is that the beams of No.2 and No.4 should be strengthened by adding steel wire or carbon fiber reinforced epoxy (CFRP) bar to their bottom surfaces. A steel wire of diameter less than 10 mm or CFRP slim bar of smaller diameter is enough to bear the most burdens.
(4) The routine inspection system for the deformation of the main beam is needed to be set up. The conventional methodologies of strain gages and/or optical glass fiber sensors can be used to detect small deformation. In case of the occurrence of abnormal deformation signal, urgent measures should be taken to prevent catastrophic event.

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