Engineering Aspects of the Collapse of the Colossus of Rhodes Statue

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ABSTRACT-The collapse of the Colossus of Rhodes statue in 224 B.C. is usually ascribed to an earthquake. Although details of this statue are available from Philo of Byzantium [1] and from Pliny [2], there appears to have been no scientific assessment as to the reasonableness of the earthquake argument. The investigation described in this paper uses the descriptions of Philo and Pliny to propose a likely model for the statue, and employs the present-day technologies of finite element analysis with representative earthquake engineering data to investigate the effects of an earthquake on the Colossus. The results shed new light on the manner in which the collapse of the Colossus occurred.

KEYWORDS: Colossus of Rhodes, earthquake spectrum, ancient technology, bronze casting, finite element engineering

THE COLOSSUS OF RHODES

The Colossus of Rhodes was a huge bronze statue of Helios, the god of the sun. It stood about 110 feet tall, possibly mounted upon a pedestal of some form, and situated close to the harbor of the city of Rhodes in the Dodecanese islands. The statue was erected by the Rhodians to honor Helios for allowing the unsuccessful siege of the city by Demetrius Poliocetes to be lifted in 305 B.C. It was designed and built during the years 292-280 B.C. by the famous sculptor Chares of Lyndos. Tradition says that the Colossus was felled by a strong earthquake around 224 B.C. The shattered pieces of the statue lay where they had fallen until 653 A. D., when they were finally broken up and sold as scrap to a merchant from Edessa, Syria. No trace remains of the Colossus today.

HISTORICAL SOURCES USED

Brief commentaries with descriptions of the Colossus have been provided by Philo of Byzantium [1], by Strabo, and by Pliny [2]. Philo was a Greek mechanist who lived in the 2nd Century B.C., included the Colossus in his list of the Seven Wonders of the Ancient World. He apparently saw the wreck of the Colossus around 150 B.C., and details from his account of its construction will be used later in this text. Pliny (Plineus Caius Secundus) was a Roman naturalist who lived in the 1st Century A.D. He died

during the eruption of Vesuvius in 79 A.D. Pliny commented on the Colossus as follows:
This statue was thrown down by an earthquake fifty-six years after it was erected. Few men can clasp the thumb in their arms, and its fingers are larger than most statues. When the limbs are broken asunder vast caverns are seen yawning in the interior. Within it, too, are to be seen large masses of rock by whose weight the artist steadied it while in process of erection. It is said that it was twelve years in the making, and that three hundred talents were spent upon it-a sum raised from the engines of war abandoned by Demetrius after his futile siege. ***(Pliny ca. 50 A. D.)***

Medieval writers devised and perpetrated the picturesque, but erroneous idea (endorsed by Shakespeare), of a 'bestride' or legs-apart Colossus which stood across a narrow entrance to the inner harbor of Rhodes. This concept is still widely depicted today.[1] General historical details concerning the Colossus and of its period, the contemporaneous eastern Mediterranean, as used in this study were obtained from a variety of sources, including Durant [3], Romer [4] and other writers. Details of the development of metal working and craftsmanship were obtained from Singer, et.al. [5] (articles by various authors), from Bronowski [6], and from the Encyclopedia Britannica [7] (articles by several authors). One depiction of the Colossus is shown in Figures 1.

Figure 1 Colossus IV Standing Near the Harbor Entrance. The Posture Resembles the Apollo Belvedere. Wood Engraving by Sidney Barclay 1875. © Bettman Archive, used with permission

PURPOSE OF THIS WORK
This essay presents the results of personal research conducted over a period of years together with thoughts and calculations into conditions which may have led to the destruction of this great statue. The purpose here was first to develop a plausible theory for the form and structure of the statue, consistent with both the ancient writings and culture of the region, and to use present-day finite element and earthquake engineering technology to explain *why* the Colossus was destroyed by that earthquake.

[1] All postcards depicting the Colossus available in Rhodes today show only the 'astride' form of the statue.

STATEMENT OF THE PROBLEM

Apart from the comments of Philo and Pliny, we know little of the form and construction of the statue, and virtually nothing concerning its destruction. We are likewise unaware concerning the details of its manufacture and assembly, aside from the same comments. As there are no remains of the statue to inspect, we are also ignorant of the details of the materials used, and of the metallurgical condition of the broken components. From these we might have learned something concerning the metalworking techniques used during construction, the casting practices used to create the component sections or plates, the assembly procedures used, and of the quality of workmanship involved. We know nothing of the manner whereby the Colossus was mounted upon its base, and nothing concerning the occurrence of those storms, winds, and minor earthquakes which must have occurred during the fifty-six years when the statue stood erect in Rhodes. Lastly, there are of course no records of that fatal earthquake which ancient writers claim led to the collapse of the Colossus. We therefore begin by determining the contemporary state of technology and of the relevant skills of workmanship and construction which existed in classical Greece, and second, we will establish those aspects of style pertaining to bronze statuary which prevailed on Rhodes at the start of the third century B.C.

EVOLUTION OF METALS TECHNOLOGY

The Bronze Age began with the discovery of copper smelting, and continued with the use of copper for the creation of an increasing complexity of utensils, tools and weapons. By 3200 B.C. the principles of alloying had been ‘worked out’ not only for a variety of bronzes, but for gold, silver, lead, antimony, tin, and also for alloys of these metals; Forbes [5]. By the close of the fourth millennium, the working of copper and other metals was widespread, annealing was understood for the relief of brittleness, and the use of bronze as stronger alloy of copper and tin was known and growing. The first copper tools (hammer-head, chisel, drift-wedge) evolved between 3500 and 3000 B.C. throughout Mesopotamia, and were followed during the next millennium by development of the (bronze) saw, the file (flat and round), and the copper-head cudgel, or club. For details of the development of mining, copper working, bronze technology, and of tool development, see various articles in Singer et al. [5].

Carbon steel was first developed in Syria, and in Anatolia by the Hittites at a time when the Hittite empire was at its prime (1800 to 1200 B.C.) and rivaled the Egyptian empire in area and power. Between 900 and 700 B.C., the technology of iron and steel advanced further with the development of water quenching to maximize hardness. Tempering to relieve brittleness did not truly evolve until Roman times (200 B.C. to 100 A.D.). During the first millennium B.C., the making of hard but ductile iron components became a consummate art, and was perfected nowhere to a finer degree than in Damascus, Syria, around the time of the Colossus. Furnace technology for iron smelting became available around 1400 B.C.. The forming of wrought iron components by forging soon followed, together with the joining of iron bars and other components by swaging. Iron swords, repaired by swaging during Roman times and possibly earlier, have been found [5], and an iron dagger was found in Tutanhkamon's tomb (1325 B.C.).

DEVELOPMENTS IN FORMING TECHNOLOGY

An important development in manufacturing technology concerns the technique of riveting. A copper pot of riveted construction was discovered during excavations at Ur in southern Iraq, dating from the period around 2500 B.C. By 2500 B.C., thin sheets of soft malleable copper were being hammered and formed into component parts for many utensils. By this time these sheets could have been cut to size by hammering over a sharpened, hardened bronze edge. A suitable punch for copper could readily have been made at that time from an antimony or leaded bronze (bronze alloying principles were then well known), and bronze tools could be hardened by working or possibly by quenching (air or water). In this manner, bronze tools for forming and punching holes for rivets could have been prepared. Finally, the components of the pot could have been joined by the hammering of soft copper rivets.

The technique of punching may have been used by the artisans of the Colossus. While cold punching of thin sections could readily have been undertaken by 300 B.C., the punching of thicker sections would probably have required a furnace for local heating for hot punching. Long pliers could have been used routinely for holding the punch at a distance while making rivet holes along edges of the adjoining sections. These sections could then be assembled using a line of rivets. The long pliers removed the worker from both the heat of the plate and the danger of the punching hammer. A massive cast hammer-head with a long fitted wooden handle would have been commonplace in those times, wielded by a skilled hammerman (as on railroad ties today). Both hot and cold bronze could have been worked in this way, probably using a cast wrought iron anvil foundation containing suitable punching die holes. It is noted that the surface finish of such punched holes could easily have become frayed or even jagged due to these punching operations. It is also likely that no steel files (and certainly no reaming tools) would have existed at the time of the Colossus, and so any jagged surfaces around the punched holes would have to be smoothed by rubbing with stone files. Such jagged edges are still likely to have retained some pattern of small radiating cracks from the punching operations. To the extent that these cracks existed, such cracks would have been logical sites for crack growth as the Colossus swayed, driven by ground-and wind-induced motions. If the method of fabrication by punching and riveting was used in the construction of the Colossus, the finished statue could have contained many cracks, some developed, some latent.

Another technology which was needed for manufacture of the components of the Colossus is mold casting. Casting is said to have begun in Mesopotamia around 3500 B.C.[5] Capabilities for molding and casting bronze implements and figures grew steadily over the next 2000 years. A tomb painting has been found at a temple in Egupt, dating from around 1500 B.C. Each door probably weighed around one ton, and possibly more (a one-inch thick bronze slab of plan 8ft x 12ft weighs two tons). By 800 B.C., casting of exquisitely detailed animal shapes had been achieved without the need for further hand finishing of surface details apart from burnishing [3]. By 500 B.C., the *cire perdue* (lost wax) process for casting of wall thicknesses of 1/8 in. or less for hollow bronze figures (of moderate to life-size, or slightly greater) was being practiced in Greece, having been developed in Syria and Egypt somewhat earlier. Durant [3] reports that Theodorus of Samos and Rhoecus introduced the hollow bronze casting process into Greece.

FORM AND POSE OF THE COLOSSUS

With the above understanding of the construction technology of the time, it is now appropriate to consider the problem of the likely form of the Colossus structure; and secondly, its probable manner of construction.

Romer [4] mentions that colossi were fairly common throughout the Egyptian, Greek, and Roman world, and he states that there are numbers of smaller, contemporaneous statues and bronzework still in existence from the period of the Colossus. There also are descriptions of at least two other huge (but again smaller) statues of gods from a somewhat earlier period available to us - the Zeus of Pheidias at Olympus and the Athena Promachos by the same sculptor[1]. These works provide useful insight into possible manufacturing techniques and capabilities of that period, and are also of value for identifying the artistic concepts which must have influenced the sculptors who designed the Colossus.

The constructional technologies needed to build such a large structure in the third century B.C. included the alloying of bronze, iron working, metal casting, metal forming, riveting, and constructional procedures for large structures. The specific skills required are again finely conditioned by the details of form and shape which were concomitant to the form selected by the Rhodian artisans for the Colossus. Both form and shape were ultimately conditioned by the vast size of the statue. The assumption of a specific form for our purpose must be made with great care, as a wrong choice can be expected to lead to erroneous results from the studies that follow. For example, although the ‘pedestal' Colossus (like the Statue of Liberty) shown in Figure 3 is more likely to be stable against ground motions than the ‘astride’ Colossus forms, this observation alone would be insufficient to accept the pedestal form as the true form. Some clues to the question of form may be obtained from knowledge of the shapes of certain statues that remain from that time, but the knowledge needed is so specific that only general guidance can be expected. Confirmation of metalworking practices used during the classical Greek era has also been obtained from workshops such as that of Pheidias at Olympus, which has been examined by archeologists. Here, the database is much more extensive. To address the question of why the Colossus fell we will therefore bear in mind the following thoughts; first, the statue was that of a male god; second, it was most almost certainly made from bronze; third, it was exceedingly tall in height; and fourth, it most likely stood on two legs. These fundamentals are in agreement with the words of Philo and Pliny, and so it seems most likely that from these witnesses the insight needed

[1] The statue of Zeus by Pheidias in 435 B.C. was 60 ft tall, was seated on a throne, and was made from gold with an ivory skin. Romer has discussed its manufacture in detail, including the workshops of Pheidias. Similarly, the bronze statue of Athena Promachos, also by Pheidias, with its pedestal rose to a height of 70 ft. This great statue had a standing draped female form, which made it much more stable and easier to construct. Helpful discussions of aesthetic style in bronze statuary during the late classical period of ancient Greece are given in the works of both Durant and Romer.

to solve the riddles of form, construction, and ultimately collapse of the Colossus can be derived.

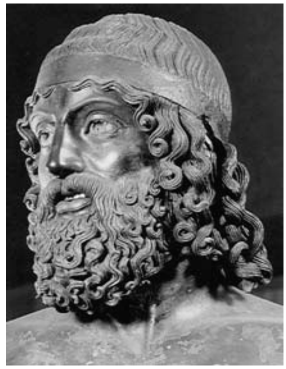

Figure 2 Warrior "A" (detail of statue, 200 cm in height) Bronze with Naturalistic Decoration C 460-450 B.C. Found in the Sea of Riace Marina, Italy. Museo Nazionale Reggio Calabria. ©Flynn [9], used with permission

Speculations concerning the pose of the Colossus fall into three categories, and these poses are somewhat related to conjectures as to where the Colossus stood. The first of these is the figure astride the harbor entrance, which despite its widespread popularity has generally been dismissed by scholars for over a century. Such a pose is now regarded as; (a) too *undignified* for a god of such importance as Helios, (b) *impractical*, because the corresponding harbor entrance could then only have been about 30 feet wide, (too narrow and too dangerous for safe passage of laden vessels in and out of the harbor), (c) structurally *unsound* for practical construction and long-term survival of the statue and (d) *too inaccessible* during the construction phase due to the extensive surrounding area required under all construction hypotheses for ramp-works, etc. Objections (a) and (b) were also recognized by Romer. Such ramp-works around an astride Colossus during construction could have blocked the flow of traffic through and around the harbor entrance, possibly for years. The astride Colossus will not be pursued further for these reasons.

The second Colossus concept was the fully draped figure, mounted on an elevated masonry pedestal, and possibly standing within the grounds of a temple complex somewhere distant from the harbor. This concept is also somewhat fanciful, but the form is structurally plausible because the legs are shown together with a draped gown (again like *Liberty* though less extensive). Such a grouping if draped to the ground can be expected to receive valuable structural support and rigidity from this added bracing. Romer rejected the draped concept as being 'more Roman than Greek' in its style. Some form of fully draped Colossus would be both plausible and attractive from a *structural* viewpoint, but a statue of a god *draped in a toga-like garment* may not be acceptable from an aesthetic standpoint, given the reverence afforded the male form by the ancient Greeks. One other deterrent is that if the Colossus was required to serve as a harbor beacon, a statue situated closer to the water would seem more likely for this purpose than one in a temple complex removed from the harbor.

The third Colossus idea, Figure 1, is a semi-nude figure standing *near* the harbor entrance, possibly upon a masonry platform near the present site of the fort of St. Nicholas. This form of this concept is similar to that of the Apollo Belvedere which was of Greek craftsmanship dating from the same period as the Colossus. The form shown in Figure 1 appears to be relatively weak at the ankles and lower legs, and its torso and arms are relatively massive. This suggests an inherent structural weakness.

For the structural analysis given in this paper, a figure with a closer-legged pose mounted on a single platform was chosen. The selected pose permits straight-forward computer modeling, but retains all the essential cultural and aesthetic aspects which would affect the dynamics of the statue. After consideration, it seemed likely that the true pose was some closer-legged version of the pose shown in Figure 1, with an aesthetic form similar to that of the Apollo Belvedere, mounted on a platform..

ANCIENT DESCRIPTIONS OF THE STRUCTURAL DETAILS

Romer [4] cites in detail specific writings from Philo of Byzantium concerning the construction of the Colossus. For detailed examination, these comments are laid out below in numbered sequence to aid the development of an hypothesis concerning the most likely method of construction used. The following statements have been taken *verbatim* from Romer, who quotes Philo as saying:

1. It was secured firmly from the inside with iron frames and square blocks of stone.
2. The horizontal bars exhibit hammer-work.
3. The hidden part of the work is bigger (*more substantial*?) than the visible parts.
4. With what workforce was such a weight of poles (*rods?*) forged?
5. The molten image of the structure was the bronzework of the world.
6. A base of white marble was laid down, and on this …
7. The sculptor first set the feet of the Colossus up to the ankle-bones.
8. The soles of the feet on the base were already at a greater height than other statues.
9. It was impossible to lift up the rest and set it on top.
10. The ankles had to be cast on top, and as it happens in building houses
11. The whole work had to rise on top of itself.
12. Artists first make a mold, then divide it into parts, cast them, and finally put them all together and erect the statue.
13. It was not possible to move the metal parts.
14. When the casting had been done on the earlier worked parts, the intervals of the bars and the joints of the framework were taken care of.
15. The structure was held steady with stones that had been put inside.
16. An immense mound of earth was continually poured round the finished parts of the Colossus, hiding what had already been done underground.
17. The artist carried out the next stage of casting on the flat surface of what was underneath.

Durant [3] and Romer [4] also attribute the following descriptive points to Pliny:

1. Few people can get their arms around one of its thumbs.
2. Its fingers are bigger than most statues.
3. Where the limbs have broken off there are huge gaping cavities.

4. Inside it one can see rocks of enormous size which Chares had used to stabilize it when he was building it.

POSSIBLE METHOD FOR FABRICATION AND CONSTRUCTION

The following guidelines were use: (a) the state of construction and fabrication technology which is outlined in the preceding sections, (b) the seventeen criteria of Philo, and (c) the four criteria of Pliny. The hypothesis, which follows is based on the above items and is here submitted as satisfying the above criteria. This hypothesis thus represents a workable concept for the fabrication and construction of the statue (C = criteria numbers with author, referred to the earlier criteria listings):

Base: A substanstial base platform of stone surfaced with marble at least 60 feet in diameter and 10 to 15 feet in height would first have been constructed. The form of this platform was possible circular or polygonal in shape. Philo, C6, 7 and 8.

Feet: The feet of the statue were built using massive blocks of carved stone. The feet were then covered with thin sheets of beaten bronze, riveted together. This stone block construction of the feet was carried up to the ankles. Philo, C1, 7 and 8**.**

Ankles: Eight or so major iron bars were each made by forging and swaging, and were set into and beneath the base structure in a horizontal, radiating pattern. The horizontal bars in the basework converged inwardly upon the ankle where they turned and became vertical. These vertical bars became smaller in diameter, and followed the shape of the statue up the feet and inside the leg. In this manner continuity, strength, and stability were imparted to the lower regions of the structure. These bars were further used to constrain the bronze outer surface plates into a continuous circular structure. Philo, C1, 2 and 7.

Legs: From the ankles up, the structure of the statue was formed from many curved, cast bronze plates joined together into circular rings by rivets, or T-clamps. These clamping devices are set into precisely- aligned, adjoining lugs or holes in the surface plates. Each plate was about 60 inches by 60 inches at the sides and about one inch thick in the lower leg, and successively less in thickness at the higher levels of the statue. These inch thick plates weigh from 600 to 1000 lbs depending on their outer detail. The higher plates were of thickness about ¼ in. or so, and they weighed correspondingly less. Philo, C7, 8, 9, 10 and 11. Pliny C3.

As the structure rose, the thickness of the plates could be reduced as the surface detail would allow, except where needed for strength (joints, loins, arm-shoulder region, etc.). Thus a 60x60x1/4 inch plate could weight 150 to 250 pounds with the same thickness of rim for strength of assembly and for the lugs which are needed for attachment. Such a surface thickness is well within the casting capabilities of that time. (No comment from Philo or Pliny).

It is here suggested that such plates may each have been cast to the particular local shape required for the statue by the artist, possibly with their vertical edges slightly angled inwards, so that when assembled the plates would readily form the circular or elliptical ring shape required by the surface shape. These plates were possibly clamped together using rivets fitted through carefully aligned holes formed during the casting process (and by punching with thinner sections), as shown in Figure 3. The metal casting technique proposed is practical and within all aspects of the technology of the time. The fine level of skill achieved during this period is shown in Figure 2. Moreover, the casting of plates could have been undertaken off-site, and the finished plates could have been transported to the site of the statue, and then assembled. The first rings of the legs could have been assembled into position and secured to the stone ankle bases. Subsequent rings could have been secured into position above the lower rings by the same riveting or T-clamping procedure. A possible casting procedure for the face of the Colosus is suggested in Figure 4.

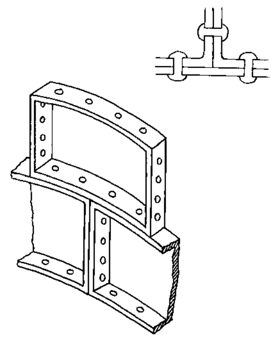

Figure 3 Details of Joining Plates by Riveting

If the structure rose on average by about 10 feet per year (two rings) up through the legs, torso, arms and head, this would require the manufacture and assembly of about 30 to 60 of such plates per year over the 12 years of construction. Philo, C11, 12, 13 and 17.
A circular mound of earth might have been built around the structure to provide access for transportation and construction. This mound could have been enlarged as the statue grew upward, but it would also grow radially outward. The size and stability of this mound could have been limited somewhat if it were strengthened by a massive wooden spiral retaining wall or fence, perhaps reinforced by forged chains or ropes. The mound might have been raised and extended outward as each successive ring of plates was completed. The legs of the structure could still have been stabilized by filling them with masses of stones, some large, some small, at least up to the knees for greatest effect. Philo C15 and 16. Pliny C4.

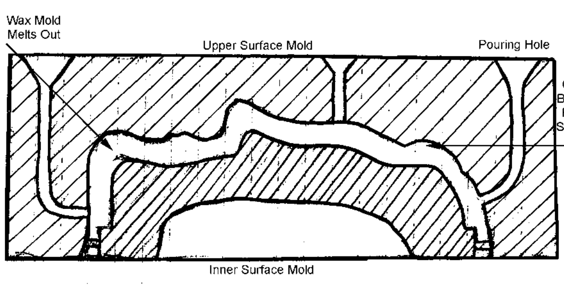

Figure 4 Details of Construction

It seems possible that many successive rings of the massive structure might first have been created as full-size wax impressions each mounted upon a central hollow core in the artist's studio near his foundry. The outer surface of each ring could then have been worked on in great detail by artists for months to ultimately create the desired form of the god. The inner surface could also have been worked on by foundrymen to develop the flanges, holes and assembly features. Upon artistic completion each molded ring of the structure could have been subdivided for final forming into many separate vertical plates about 5ft x 5ft in size. The completed molds for each of these plates could then have been poured individually in the foundry using the *cire perdue* process, to create the required of interlocking bronze plates for the statue.
Philo in Comment 16 mentions the 'mound-of-earth' idea for the construction process, for which there are precedents in the ziggurats of Mesopotamia and likely with the pyramids of Egypt. But though it is a practical possibility, a stabilizing surrounding circular ramp could require stout retaining walls (perhaps of wood, bound by ropes or chains), plus an extensive adjacent area upon which the earth mound might grow outward. A clear circle of about 300 ft or more in diameter would be needed to reach the top of the Colossus, with a 30° angle of repose for the soil. And of course a *vast* amount of earth fill. Such an area is larger than the footprint of the present fort of St. Nicholas at the end of the sea wall of Mandraki harbor. Romer has mentioned the possibility that the great wooden towers left behind from the siege of Demetrius 15 years before may have been transported to the site of the Colossus, and might have been used in its construction. One tower is said to have been 100 ft tall, 200 ft long, and possibly 75 ft broad. Stripped of its armor and engines of war, such a huge platform would appear to constitute a very useful assist for the peacetime construction of another tall structure of similar height.

NATURE OF EARTHQUAKE LOADING

Earthquake loading is not pure-harmonic in nature. Typically it is spectral (multiple-frequencies) and transient in time. That the Colossus was felled by a strong earthquake is widely accepted, and it is also known that the terrain of the Aegean and of Asia Minor contains is generally rocky. One strong earthquake which is well-documented in its time-history, and which also occurred in rocky terrain is the El Centro, California earthquake of 1940. This earthquake is relevant because it took place in ground similar to that of the terrain of Rhodes. Acceleration, velocity, and displacement vs time traces of the surface horizontal motion from this earthquake are shown in Figure 5, from Newmark and Rosenbluth [10]. Nothing, of course, is known concerning the Rhodes earthquake of 224 B.C. Its strength, duration and directional properties remain as mysteries. The El Centro earthquake registered around 8.0 on the Richter (modified Mercalli) scale, i.e., of similar strength to the San Francisco (1906) quake which is to have measured Richter 8.1.
It was ultimately decided that the most representative earthquake excitation at the Colossus site could be best defined by using a median Newmark-Hall forcing spectrum anchored in a 0.30g zero period ground acceleration (ZPGA). This spectrum is the normalized average of many earthquakes in similar terrain. This excitation was applied with equal strength in two orthogonal horizontal directions, and the applied vertical peak acceleration was assumed to be 2/3 of the horizontal peak accelerations. The Newmark-

Hall spectrum is widely used as representative in a probabilistic sense for firm soil sites all over the world, including Asia and Europe. Having in mind the physical uncertainty related to the definition of the seismic hazard at the Colossus site, the acceptance of a median Newmark-Hall spectrum appears to be most reasonable for present purposes. Two Newmark-Hall analyses and two El Centro (1940) analyses also were performed, and as with the Newmark-Hall spectrum using 2 percent and 5 percent equivalent damping for the statue structure. Lastly, it was verified that the shape of the spectrum is consistent with other earthquakes, which have occurred in the Aegean area.

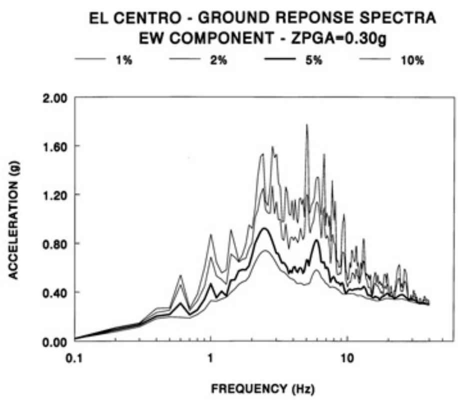

Figure 5 El Centro (1940) Acceleration Spectrum

FINITE ELEMENT MODEL

A representative computer model of the Colossus was created using the solid modeling capabilities of the ANSYS [11] code; see Figure 6. The structure was modeled as a surface continuum of plates, with identical boundary displacements and slopes throughout. The legs were modeled as a series of nine hollow circular cones per leg, as shown in Figure 8. The lower abdomen was represented by three hollow elliptical cones while the upper part of the abdomen was created using a series of four hollow elliptical cones. In order to model the chest, two hollow elliptical cones were used. The shoulders were next created with a series of five hollow partial-circular surfaces between the front and back portions of the chest. Next, the head was created (as a hollow sphere) together with the neck, as a hollow circular cylinder. The head and neck were then overlapped together with the shoulders using the Boolean capabilities of the ANSYS code. Finally, the arms were modeled using hollow circular truncated cone sections,

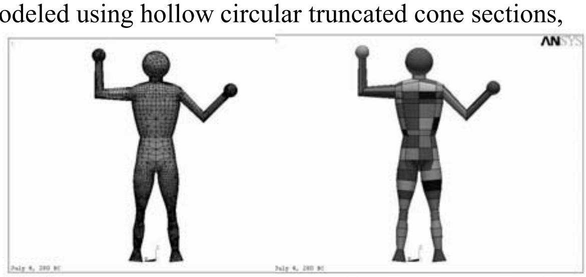

Figure 6 Finite Element Mesh

ending with an overlapping hollow sphere at each end of each arm, representing the hands. The arms were angled between defined spatial points at each elbow and wrist. After consideration, the system of iron rods was not included in the model.
Different values of plate thickness were assigned to various regions throughout the Colossus model as follows:

legs and feet-cones below knees	1.00 in
legs above the knee	0.75 in
lower abdomen	0.50 in
upper abdomen	0.50 in
shoulders	0.50 in
arms	0.50 in
neck and head	0.50 in

The geometry was converted into a finite element model using the ANSYS Automatic Mesh Generator capability. This technique automatically led to the model shown in Figure 6, which comprises 11004 shell elements and 6552 nodes. It was assumed that the statue was made of bronze for which the following mechanical properties were selected in the analyses, Marks [14]:

Young's modulus	15×10^6 psi
Poisson's ratio	0.32
Density	0.332 lb/in^3

It was assumed that below the knee the lower part of the leg contained rock fill. This condition was incorporated into the model by changing the density of the leg material below the knees. This was done to represent the mass of the rocks without adding stiffness to the model. Using a rock density of 150 lb/ft^3 and a fill/volume ratio of 0.75 for the leg and 0.9 for the foot, the density in the foot section was changed to 2.195 lb/in^3, while that of the leg it was altered to 1.882lb/in^3. The rocks in the leg were of great size (Pliny), which is likely to have made the fill ratio less than in the foot, where the stone was carved and consequently the fill was more complete there (Philo). Finally, the feet were represented by short conical sections, the soles of which were constrained against both displacement and rotation to simulate the effect of the rugged stone-and-iron foot and foundation structure, and of the foundation itself, on the motions of the Colossus.

FINITE ELEMENT ANALYSIS

Static Stresses

Static stresses in the model were first computed under gravity loading. Generally the largest stresses were found at the joints of the arms and legs. Away from the joints the stresses were always lower. The maximum stresses occurred in the arms and shoulder joint were due to gravity bending. Von Mises stresses of about 48 KSI were found in these regions. Static gravity stresses above the knees and in the legs and ankles were found to be in the order of 3.3 KSI.

Natural Frequencies and Mode Shapes

Natural frequencies and vibration mode shapes were calculated for the statue. The shapes of the lowest two modes are shown in Figures 20 and 21. Properties of the first ten natural modes are described in the following table with their corresponding frequencies.

Mode	Frequency Hz	Shape of Mode
1	0.6702	front/back oscillation
2	1.2747	up/down oscillation of left arm
3	1.4992	twisting of both arms and shoulders
4	2.0721	up/down oscillation of right arm
5	2.2418	front/back movements of both arms in-phase
6	2.8176	right arm side-ways oscillation
7	3.4378	left arm side-ways oscillation
8	4.4742	twisting motion of whole body
9	5.0951	right arm and upper body up/down motion
10	5.3605	body twist around waist, no arms movement

Spectral Dynamic Response Analysis

The model Colossus was subjected to seismic excitation applied at the base of the platform. The main seismic spectrum used was a median Newmark-Hall ground response spectrum having a peak ground acceleration of 0.3g. This excitation was applied in all three X, Y and Z directions, with relative strengths in the ratio of 1, 1 and 0.67. Two different spectra were applied to the model. These spectra represented the ground acceleration applied at damping ratios of 2 percent and 5 percent respectively. The spectrum results were determined as the Square-Root of the Sum of the Squares (SRSS) of all the contributing modal stress responses.

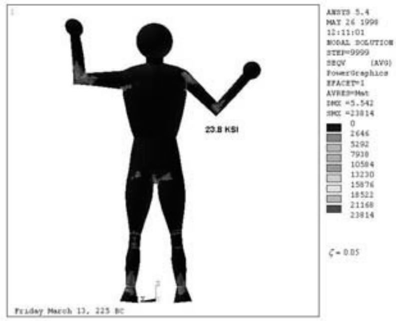

Figure 7 Maximum Dynamic Stress Response to Acceleration Spectrum. All Modes

The maximum spectral Von Mises (SRSS) stress found by this method was ±23.8 KSI. This stress occurred in the elbow joint, as shown in Figure 7. The corresponding (SRSS) stress in the ankle was ±13.4 KSI, while that above the knee was ± 9.0 KSI. These results are shown in Figure 8. Again, low spectral dynamic stresses were found throughout the body of the Colossus. This clearly indicates that without the presence of substantial reinforcing construction in the body joint regions, the first signs of damage from earthquake forcing can be expected to occur in the vicinity of the body joints. Hand calculation showed that such stresses could have been reduced by a maximum of about six percent by the proposed system of vertical iron rods.

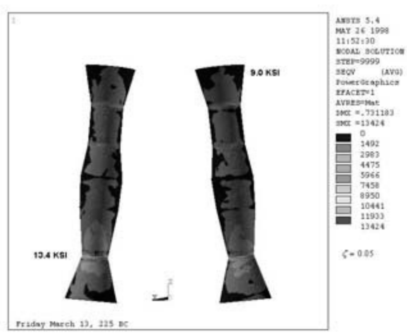

Figure 8 Acceleration Stresses in Legs

DISCUSSION OF STRESSES AND OF FAILURE POTENTIAL

1. How failure by earthquake ground motions influenced form and pose of the statue.

A seated colossus form is not likely to have broken at the knees or ankles because the throne and feet would likely represent a more substantial and stable restraint. A standing, draped female form (like *Liberty*) would be more resilient for the same reasons. A male form draped to the ground is not likely to have been the form of the god. Statues of male gods in Hellenist Greece were characteristically nude, especially when standing.[1] A standing nude form was frequently braced at the leg to impart stability (the Apollo Belvedere), and though such bracing was *possibly* used with the Colossus, this form seems less likely, because if the statue were situated near the harbor to serve as a welcoming beacon, the sculptor's desire to portray the beauty of the god would have been encumbered by such attachments. Internal reinforcement therefore seems *much* more likely, and perhaps this is why the iron bars are mentioned by Philo. Thus it appears that the most likely form was also the one with potentially the least structural stability. The action of an earthquake on such a statue is unlikely to have been mitigated to any extent by leg bracing, because if such bracing were effective, it would have stiffened the frequency of the destructive lowest mode *directly into the greatest strength of the excitation spectrum*: see Figure 5. The strong excitation region lying between 1.0 Hz and 5.0 Hz is sufficiently broad that the stiffening of one leg is unlikely to have saved the structure. The arms would still have failed, and probably the unstiffened leg also, thus bringing down the remainder. Similarly, removing mass from the upper levels of the statue by using thinner plates would also have increased the lowest natural frequency into the strongest excitation region. Height and chosen form were thus the major aesthetic factors which influenced the collapse of the Colossus.

2. The internal fastening procedure must be both constructable and practical for the times.

Given the proposed construction using cast plates, and accepting that these might have been crafted for assembly by grinding the mating surfaces with stones, only a limited number of assembly techniques are available. Assuming consistent skilled craftsmanship (but not necessarily precision), rivets appear to be the most likely selection for fasteners between the surface plates. They could be manufactured in great quantities off-site by mold casting - one head, and a shank for peening. There were of course no bolts; the metal screw thread dates from as recently as Leonardo da Vinci's era. Another possibility was the clamp, which had a two-headed cross section (like a peened rivet), but needed to be inserted from the outside into an open slot, cut into the two mated surfaces. Clamps obtain their clamping action from shrinkage after being inserted while hot.[2] This shrinkage typically gives rise to high residual tensile stresses. Clamps are considered less likely for the Colossus because they would have been less convenient to manufacture and install, and required greater precision. The rivet therefore emerges as the most likely fastening used in the Colossus, for reasons of convenience, of manufacture, and of installation. A simple installation procedure would have been to heat the rivet tip in a brazier at the site, then install it in the mating holes using a pair of tongs, and then to peen down the second head, using a metal anvil or a large rock to absorb the transmitted peening blows. When the rivet cooled, the joint would have clamped tight from the residual tensile force developed by the shrinkage.

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[1] Such was the level of respect for athletic male forms and for the greater deities among Greek sculptors that a standing god offered the greatest scope a sculptor to demonstrate his skill in depicting the sublime beauty of the divine form. As the architect of the Colossus was an eminent sculptor of the day, it seems certain that veracity of form in the statue must have powerfully influenced Chares' choice for Helios's form.

[2] Clamps were widely used throughout ancient cultures. Mayans and Incas used them to bond stones together, by pouring molten metal into matching carved slots in the two mated components [13].

3. What was the net effect of all likely loads acting on the knee joint rivets.

The loads acting on the cross-sections of the knee joint rivets consist of combinations of the following forces:

Static Loads

Gravity	~ 2 KSI on flanges
Horizontal Wind	~0.5 KSI from 30 mph wind
Rivet Shrinkage	+15.0 KSI from 500°F shrinkage

Dynamic Loads

Horizontal Wind	~ ± 0.5 KSI from 30 mph wind
Earthquake	± 45.0 KSI average 0.3g acceleration

The most significant static load evidently results from rivet shrinkage. This load is expected to impose local strains beyond the yield strength of a well formed tight-fitting rivet. An even greater region of yielding can be expected to develop at the shank/head fillet radius. In some locations, the compressive load of gravity may slightly relieve some of the rivet tension..

The most important rivet dynamic load is the earthquake load S_{fem}, which was found to lie somewhere between ±30 KSI and ±100 KSI (elastic), depending on rivet diameter and number. An average elastic dynamic stress of ±45 KSI was used for making rivet strain estimates. This dynamic strain alone would be sufficient to yield the outermost rivet to failure (cracking) at the rivet head fillet in very few load cycles. Repeated cycling could be expected to propagate such a crack to failure in a short period of time, noting that upon cracking (or even substantial yielding) the load is expected redistribute to other rivets, until they too cracked. Combining a high static stress with the high earthquake load would further hasten the development of this cracking mechanism.

SUMMARY

Ample sources of high stress loading combinations sufficient to eventually cause rivet failure existed in the day-to-day conditions surrounding the Colossus. Such dynamic plus static load combinations existed during the fatal earthquake, and these must have been well able to cause significant rivet yielding. High static residual stresses may also have existed in the copper rivets following manufacture, especially in the rivet head fillets. Load shedding due to yielding would have spread the high cyclic loads to other rivets, and likely caused these rivets to crack also.

When the extreme fiber rivets failed, the rivet failures could thus have cascaded until the structure broke up at its joints (arms, legs, knees) and toppled to the ground. The Colossus likely shattered at several locations during the quake, as noted from the multiple sites where high dynamic stresses existed. The fundamental breakup most likely occurred while the statue was standing and whole, though further destruction undoubtedly occurred when the pieces hit the ground.

CONCLUSIONS

1. An El Centro (1940) strength earthquake could have brought down a Colossus of traditional size and form, built with the constructional details described in the paper.

2. The most probable primary cause of the collapse of the statue was the inherent weakness of wrought copper as a joint material, and possibly the manufactured quality of the cast rivets and holes.
3. The weakest points of the Colossus under earthquake conditions occurred where the joints were located. Stresses in the body and limbs away from joints were low.
4. The arm-body joints were the highest stress locations, from both gravity load and from the earthquake dynamic load. It appears likely that an arm, or arms, would have failed first.
5. The ankle joint was also a critical location. The survival of this joint would appear to have depended on the constructional details of the ankle joint, the quantity of iron used there, and the quality of detailed workmanship employed. Copper rivets at this location seem certain to have yielded under earthquake loading.
6. The knee joint is less vulnerable than the ankle, but the actual distribution of stresses between these locations would depend greatly upon the internal strengthening details employed.
7. All major technologies required to build a metal Colossus were available in 290 B.C. The required constructional procedures and techniques were also available, and had been successfully demonstrated on other statues and structures prior to this time.
8. The construction method proposed herein is plausible for the times and is consistent with the writings of Philo and Phiny.

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