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Design Considerations for the CHARA Optical Delay System Mechanical Support Structure[2]

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1. INTRODUCTION TO THE CHARA ARRAY PROJECT

The Center for High Angular Resolution Astronomy (CHARA) of Georgia State University will build a facility for optical/infrared multi-telescope interferometry, called the CHARA Array. This array will consist of initially five (with a goal of seven) telescopes distributed over an area approximately 350 meters across. The light beams from the individual telescopes will be transported through evacuated pipes to a central laboratory, which will contain optical delay lines, beam combination optics, and detection systems. The facility will consist of these components plus the associated buildings and support equipment, and will be located on a mountain site in the southwestern United States. The CHARA Array is funded by Georgia State University and the National Science Foundation. An extensive collection of technical reports can be accessed through CHARA's WWW homepage: (http://chara.gsu.edu).

2. OVERVIEW

The CHARA Array variable optical delay will consist of two parts — a switchable segment delay, called PoPs, for *Pipes of Pan*, (the name reflecting a whimsical impression of an initial concept); plus a continuously variable delay achieved with retroreflectors on wheeled carts, called here OPLE's, or *Optical Path Length Equalizers.*

For full sky coverage, the optical delay required is approximately equal to the maximum separation between telescopes, or about 300 meters in the CHARA Array. Since the additional reflections required of a multiple pass system would cause increased light loss, this solution will be avoided to the extent possible. Therefore, housing the 300-m optical delay becomes a serious problem with respect to cost, and even acreage.

This report describes some of the conceptual and detailed mechanical considerations that underly the adopted optical delay implementation.

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[2]This report mixes English and metric units somewhat ungracefully. We regret the inconvenience to readers.

3. FIXED VERSUS VARIABLE DELAY

In order to offer a continuous observation window of at least 30 minutes of time on the longest E-W baselines near transit at zenith, the continuously variable optical delay must be about 35 meters. Coordinating overlapping observing windows with multiple telescope pairs will require some additional optical path for flexibility of delay line scheduling.

A similar argument leads to the conclusions that a segmented optical delay should have an incremental segment length of about 35 m.

The costs of continuously variable optical delay and segmented delay scale differently. The continuously variable delay requires a fixed investment in optics and electronics, then a per meter additional cost in the enclosure and pier/rail costs. The segmented optical delay, neglecting design costs, has a per segment cost which depends on the additional hardware required for each segment station. Based on estimates for the various costs, it was found in the CHARA case that the minimum cost occurred for a continuously variable delay of about 70 m total delay[3].

4. VACUUM VERSUS AIR DELAY

It has generally been assumed that the advantages of vacuum for optical delay are in the better balance of longitudinal dispersion and the lessened sensitivity to seeing within the array optical path. Recent experience at IOTA has shown that a very important advantage of vacuum delay paths is reduced alignment errors caused by variable stratification of still air. Yet another factor which may be overlooked is the greatly increased longevity of the high reflectivity optical coatings required to combat efficiency losses in the long optical chain of most interferometers.

In short, there are a number of very significant advantages to vacuum optical delay lines. The only reason for using air optical delay paths is cost reduction.

CHARA has chosen to compromise on this issue. The segmented delay is planned to be housed in vacuum, and the continuously variable delay in air.

5. HOUSING THE OPTICAL DELAY

The continuously variable optical delay must, of course, be in a laboratory environment. The segmented vacuum delay could, in principle, be in less controlled environment.

Initial, blue sky concepts for the CHARA Array layout placed the segmented delay lines (PoPs) at right angles to the continuously variable delay (OPLEs). This is the most efficient in the number of optical surfaces.

CHARA's selection of the Mt. Wilson site immediately ruled out this concept, as the site did not offer the opportunity of laying out such a configuration, and the non-planar telescope locations was inconsistent with the optical configuration required to minimize the number of optical elements. Hence it was decided to run the PoPs parallel to the OPLEs.

[3] CHARA Technical Report No. 4.

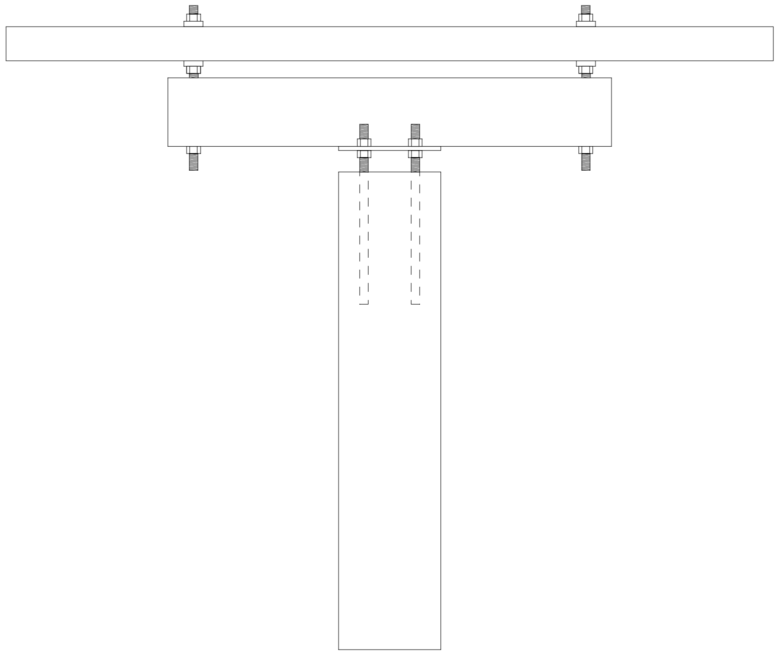

FIGURE 1. End view of OPLE support T system, showing concrete beam, crosspiece and sleeper. The sleeper will support two sets of rail shafts, and two OPLE carts, side-by-side. The corresponding two PoP vacuum pipes will be installed at floor level, one under each side of the T.

The total planned PoP physical length is about 100 meters, twice the physical length of the OPLEs (about 50 meters). This could have been solved with a 50-m enclosure, and the PoPs extending into the outdoors, or perhaps into a minimal enclosure. It was decided to extend the enclosure to the full length of the PoPs. The incremental cost was moderate; the advantages of having all PoP optics in a controlled laboratory was reassuring with respect to stability of alignment from day to night; and the additional enclosed space looked very helpful as a staging area for assembly and installation of the OPLE systems.

6. DEPLOYING THE OPLES AND POPS

The decision to house the OPLE and PoP delays within the same enclosure proved to be a severe and unforeseen constraint. Stacking the OPLEs and PoPs in a space-efficient way either requires additional optical surfaces, severely limits access of personnel for installation and maintenance, or greatly restricts the options for the mechanical infrastructure which support the OPLEs and PoPs.

The configuration selected places the PoP vacuum pipes at floor level, and the OPLEs on tables at working height. In order to have convenient access to the OPLEs, they were arranged in pairs, with a walkway between pairs. In order to have access to install and remove the PoP vacuum pipes (including, especially, replacement of vacuum seals) the OPLEs were installed on T-shaped tables (see CHARA Technical Report No. 58).

The approach to the OPLE installation will be to think of the tops of the T's as a sparsely populated optical table. The goal of the support design will be to construct this optical table in a way that will be at once sturdy and accurately adjustable,

7. THE OPLE/POP ENCLOSURE

The enclosure for the OPLEs and PoPs consists of a double building. The general shape is of an L, with the optical delay in the long arm and the beam combination laboratory in the short arm. Recognizing its function, the building is called the Beam Synthesis Facility.

The outer building is a conventional steel frame and panel structure. The inner building is a free-standing, aluminum framed, sheet rock covered structure. Both buildings are well insulated. Heating and cooling systems recirculate air in the plenum space between buildings only — the inner building is self-stabilized by thermal inertia.

Considerable attention was given to the footings of the BSF. All optical equipment in the beam path will be installed on massive inertia blocks, of about 60-cm thickness. These blocks are separated from the building floor and foundations by gaps, initially air gaps, subsequently plugged with a pliable sealer material. The expectation is that these inertia blocks will be relatively isolated from building vibrations and to first order from surface waves.

8. MECHANICAL DESIGN OF THE OPLE SUPPORT

The OPLEs employ catseye retroreflectors. These are chosen because they offer a significantly reduced sensitivity to errors in the OPLE translation system. The primary characteristic is that for a properly focused catseye, the return beam direction is independent of tilts and translations of the catseye. The independence is not perfect, however. Translations of the catseye result in a doubled translation of the returned beam and a resulting potential reduction in interferometric efficiency if the final beam overlap is compromised. For imperfect catseye focus, there will be changes in the returned beam direction, also reducing interferometric efficiency.

Consequently, it is desired to reduce the irregularities of the catseye translation system to a minimum. The actual requirements are related to the required interferometric efficiency through a non-trivial error budget. In keeping with CHARA practice in some other areas, the specifications will be an intuitive compromise between what is desired and what appears to be cost-effective.

Based on previous experience with delay lines for interferometry, the goal for final alignment of the OPLE trajectories will be 1 mm over the 50 meter physical travel, and 0.1 mm over any 1 m of travel (corresponding to $20''$ pitch and yaw of the catseye).

The goal in the mechanical design of the OPLE support structure is to keep mechanical flexures smaller, so that most of this error budget will be available to the alignment process. In practice, an attempt was made to keep each component of mechanical flexure to no more than 0.025 mm.

9. A SYSTEM OF OPLE T SUPPORTS

The system of inertia blocks for the OPLE/PoP system consists of a series of concrete blocks at intervals of 20 ft. The OPLE support system must bridge the 16-ft clear span from block to block, as well as providing a flat top surface for installation of the OPLE rails.

9.1. A Quick and Dirty Design of a Steel Table

Steel is the standard choice for heavy construction and it was considered first. Here is an order of magnitude design and costing for a steel T table system.

Assuming a free length of 16 feet, keeping flexure to less than 0.001 inch requires a beam moment of 500 in^4. Select a single I-beam with a 20-in high web, a 6.25-in wide flange, and 65-lb/ft weight, having a moment of 1169 in^4. For the table top, assume a single flat plate. Limiting flexure to 0.001 inch can be achieved with a solid plate 1 inch thick. The total steel required for the full OPLE installation would be about 120,000 pounds. An installed price for steel of \$0.75–\$1.25/lb would suggest a total cost in the range \$90000–\$150000. The cramped working space for installation would very likely lead to significant increases in the cost.

The simple concept could be improved to significantly reduce materials, but this would result in a corresponding increase in complexity and increased fabrication costs.

9.2. An All-Concrete T Table

As experience was showing that concrete work on Mt. Wilson was quite cost-effective, an all-concrete T structure was considered next. The concept was to pre-cast T form table sections. A temporary, flat casting surface would be prepared, and the table sections fabricated in groups. They would be stored on-site, and then transported into the BSF and grouted in place.

This approach was pursued in some detail, leading to a cost estimate of about \$130,000. The high cost was due to a number of construction issues, including the difficulty of finding storage space near the installation site, the risk of turning the tables over for installation, and the need to fabricate a custom transport rig to move the tables into position.

9.3. The Composite Concrete-Steel System

A compromise concept was explored, with a concrete beam forming the upright part of the T, and steel forming the horizontal part of the T. Use of concrete greatly increases the stiffness, and the cost is moderate. This solution was adopted. An analysis of the flexure for the passage of an OPLE cart follows.

Starting with a formula for the deflection of a simply supported beam from Hool and Pulver (1937),

$$D = c_1 \ \alpha \ \left(\frac{W \ l^3}{E_s \ b \ d^3} \right) \quad , \tag{1}$$

where $c_1 = 1/48$ for a simply supported beam with a load W concentrated at the midpoint.

The factor α is a coefficient which depends on p, the ratio of steel cross-section to concrete cross-section), and n, ratio of E_{steel} to E_{concrete}. For $p \approx 0.02$ and $n \approx 10$, $\alpha \approx 80$.

- l is the length of the beam (240 inches).
- b and d are the width and depth of the beam (12 inches and 30 inches).
- E_S is the modulus of steel (5×10^7 lb/in^2.

For the load, W, we will take 200 pounds, assuming two carts simultaneously supported in the center of the same beam. This leads to a deflection of 0.00028 inches, or 0.007 mm.

Obviously the self deflection of the beam due to its weight is much larger, but it will be taken out in the OPLE alignment process.

Concrete has some unpleasant properties with respect to cracking and creeping. As best we have determined, this can be expected to decrease with age, and the beams should be fairly quiet after about one year.

Over the approximately 50-m length of the OPLEs, it is necessary to consider carefully the possible impact of thermal expansion. CHARA did not have the resources to predict in detail the seasonal variation of the floor temperature. Also, it must be considered that the temperature could vary by tens of degrees if the building temperature were left uncontrolled and then restored, or if for reasons of economy the plenum temperature is set differently from summer to winter.

A contractor's consulting engineer recommended fixing one end of the concrete beams, and allowing the other end to slide in a mount constrained laterally but not longitudinally. A concern is that this motion would take place in a stick-slip fashion, resulting in impulsive disturbances to the entire site. This effect can be estimated. The force built up in an expanding element, F_e will be given by,

$$F_e = \frac{K \Delta_l A}{l} \quad , \tag{2}$$

where K is the spring constant, given by the modulus of elasticity, or Young's modulus. The force, F_f, required to break the starting friction, can be estimated as,

$$F_f = c_f W \quad , \tag{3}$$

where c_f is the coefficient of static friction and W is the weight of the beam supported on the sliding surface. Setting F_e equal to F_f and solving for Δ_l,

$$\Delta_l = \frac{c_f W l}{KA} \quad . \tag{4}$$

For the case of the concrete beams, the approximate values are:

- $A = 120$ in^2
- $K = 4.5 \times 10^6$ lb/in^2
- $c_f = 0.5$
- $W = 4000$ lb
- $l = 240$ inches.

This gives $\Delta_l = 0.001$ inch for the approximate beam expansion required to break static friction and initiate a slip of approximately the same magnitude. The temperature differential required to generate this expansion of the beam will be found from,

$$\Delta_T = \frac{c_f W}{K \sigma_T A} \quad , \tag{5}$$

where σ_T is the coefficient of thermal expansion.

For $\sigma_T = 5.5 \times 10^{-6}$ inch/inch/°F, the temperature change will be $\Delta_T = 2$°F. With 80 concrete beams, a drift of 1°F would result in about 40 slip episodes.

A trivial solution was available which should reduce the incidence of stick-slip to zero, and simultaneously avoid any build of significant compressive force due to beam expansion. The solution adopted is to fix one end of each beam, and support the other end on a flexure mounting. This was achieved by the rather simple expedient of leaving exposed the re-bar which connects the beam to the inertia block, so that it can flex. Over the small flexures actually expected, the flexures are effectively elastic and the lifetime of the flexure is not a concern.

Several installation strategies were considered, including fabrication in Los Angeles, fabrication at a staging site on the mountain, and casting in place. Casting in place proved the least expensive. Unfortunately, the building contractor refused, for safety reasons, to allow the installation of the concrete beams before completion of the enclosure, but this proved to be a minor inconvenience. A single set of forms was procured, and the four rows of beams were cast in four pours.

10. THE CROSSPIECES

In order to construct the synthesized optical table as required, the approach taken was to divide the problem into one of strength and one of accuracy. The strength is provided by a system of steel crosspieces, consisting of steel box beams.

The spacing of the box beams is determined by the strength of the rails on which the OPLEs run. The rails are 1.5-inch diameter steel shaft manufactured by Thomson Industries[4].

These shafts can be supported over their full length on extruded aluminum support rails, greatly increasing their strength. However, the supports can more than double the cost of the shaft system. CHARA has chosen to install the shaft on 2-inch sections of support rail at fixed intervals, and the shaft is self-supporting between these points.

The deflection of such a shaft between two support points separated by distance l can be estimated from the expression for deflection of a fixed beam (Eschbach, 1975, p. 519),

$$y = \frac{W\ l^3}{192\ E\ I} \quad , \tag{6}$$

where W is the applied force, E the modulus of elasticity and I the moment of the shaft. Adopting the following values,

- $y = 0.001$ inch (the deflection goal)
- $W = 15\,\text{lb}$ (per wheel of the OPLE cart)
- $E = 29{\times}10^6\ \text{lb/in}^2$
- $I = 0.0156\,\text{in}^4$ (for 1.5-inch diameter steel shaft).

it is possible to solve for the maximum spacing $l = 18$ inches. For reasons of economy, it was decided to adopt a spacing of 24 inches. With the 2-inch wide shaft support rail sections used, the clear span is $l = 22$ inches, indicating a shaft deflection of 0.0018 inches, or 0.05 mm.

[4]The use of Thomson products by CHARA does not constitute an endorsement. See CHARA Technical Report No. 60 for comments on quality control problems.

The deflection of each box beam can be estimated from the case of a beam with a fixed end and a cantilevered load. The deflection will be ((Eschbach, 1975, p. 519),

$$y = \frac{W\ l^3}{8\ E\ I} \tag{7}$$

Adopting the following values,

- $y = 0.001$ inch (the maximum deflection)
- $W = 30\,\mathrm{lb}$ (per single end of the OPLE cart)
- $E = 29{\times}10^6\ \mathrm{lb/in}^2$
- $l = 8.5$ inches.

it is possible to find that the required moment for the crosspiece is $I = 0.079\,\mathrm{in}^4$. A common and inexpensive tube size is 4-inch square steel tube with 0.25-in walls, which has a moment of $0.3\,\mathrm{in}^4$, which is clearly satisfactory, limiting deflections of this component to about y=0.00025 inches, or 0.1 mm.

The 4-inch square box beams constitute the support level for the synthesized optical table. Each beam is installed on the concrete T with an array of four bolts. The box beams were painted, installed and adjusted by the contractor to within normal construction tolerances of 1/4 inch, or 0.6 cm.

The complete concrete beam plus steel crosspiece system, including installation and alignment of the crosspieces, but not including design, cost about $96000.

11. THE SLEEPERS

Ideally, one could imagine crosspieces with an accurately machined top surface, adjusted into position to serve as the synthesized optical table. There are several problems with this. First, steel used in structural members, i.e., designed for strength, is not well suited for accurate machining. Such steel is not very accurately fabricated, and machining it can be expected to release stresses which will change the shape as it is machined. Clamping an irregular piece in place for machining is also a difficult process. The second problem is that an adjustment system designed to accommodate adjustment of up to about 1 cm travel is not very well suited for making small adjustments. For optimum strength, the crosspieces should be grouted to the concrete beam, which would preclude subsequent fine adjustment. Finally, the low carbon steel used in structural members is prone to rapid rust.

In order to achieve the required accuracy of the T surface, a second level of steel was installed. These are called sleepers, in analogy with the railroad sleepers, or ties, which support train rails. For these sleepers, a higher carbon steel was chosen to improve longevity. While cold-rolled steel has some attractive features, it also contains stresses which are released when the surface is machined. Therefore, hot-rolled steel was selected.

Machining the sleepers was a potential cost problem. They required a combination of through and threaded holes, plus a smooth, flat top surface. In order to save machining costs, it was decided to have the material Blanchard ground. This is a very standard technique. It consists of passing a flat metal plate or bar between counter-rotating, flat grinding wheels. The resulting piece is relatively flat and smooth. Our inquiries led to an estimate that Blanchard grinding would produce sleepers which were flat to about 0.15 mm over the sleeper length.

The decision to use the pieces machined in this way could be considered questionable. Since Blanchard grinding is usually a preliminary to further machining, the resulting quality may be uneven, and in any event is not guaranteed. Furthermore, the "expected" deviations from flatness are relatively large. If the peak error is due to a uniform curvature, and if successive sleepers are curved alternately convex and concave by the maximum expected amount, then after the sleeper heights and levels are adjusted optimally, the sleeper to sleeper variation in OPLE rail height could be on the order of 0.04 mm. This already uses up most of the OPLE alignment error goal of 0.1 mm per meter.

The cross-section of the sleepers and the spacing between them is chosen to limit deflection under the weight of the OPLEs to the specified range. The selected material, based on cost, availability, and material properties, is A36, hot-rolled, solid steel bar, 2×3 inches. This is a medium carbon steel. It will be much more rust resistant than the low carbon structural steel of the crosspieces, but they will rust in the laboratory environment unless protected. Since the top surfaces serve as a contact support surface for the rail shaft supporting hardware, the sleepers will be maintained with a layer of lubricant. Painting of the other surfaces would be possible, but tedious.

The deflection can be estimated from Equation 7, with:

- y = 0.001 inch (the maximum deflection)
- W = 15 lb (per single wheel of the OPLE cart)
- $E = 29 \times 10^6$ lb/in^2
- l = 9.5 inches (distance of the shaft from the sleeper support point)
- $I = 2\,\mathrm{in}^4$

and is y=0.00003 inches, which can be neglected.

In planning, a quote for the steel of the sleepers was $34 each (in quantity), and the cost of Blanchard grinding was $9.75. The final contractual cost, including material, grinding and other machining, and delivery, was $96 each. An estimate was obtained for applying a coating of electroless nickel, 0.0005-inch thick, to limit corrosion. The cost was $24 each, and in addition would have required special handling of a rather large quantity of material (about 27,000 lb). This option was not exercised, though it would have been nice.

12. TOTAL STRUCTURAL CONTRIBUTIONS TO ALIGNMENT ERROR BUDGET

The total structural contributions to the OPLE alignment error are collected in Table 1 in a crude error budget. Since the deflections combine systematically, a straight sum of the terms is used to estimate the total error, 0.10 mm. This is over the 60-cm spacing between sleepers. This still does not include alignment errors or drift. Thus it is likely that the goal of 0.1 mm per meter will not be achieved.

Since the goal is a soft requirement[5], and the actual performance may differ from the

[5] That is, it depends on the *as built* performance of other components for which a cost-performance trade has not yet been carried out.

approximate calculation, no amelioration is planned initially. If the alignment is slightly inadequate, the largest contributor to systematic error, the shaft deflection, can be easily reduced to near zero by installing shaft supports over the full length of the shafts instead of just at the sleepers. Using the manufacturer's product for this purpose, equipping the OPLEs for the first five telescopes would cost about $56,000. Since this is an easy retrofit and an expensive improvement, it will be deferred unless proven necesary.

TABLE 1. The OPLE alignment errors due to the T support structure and the OPLE rail shafts.

Contributor	Deflection or Error (mm)
Concrete Beam Deflection	0.007
Shaft Deflection	0.05
Crosspiece Deflection	0.006
Sleeper Deflection	0.00075
Sleeper Convexity Error	0.04
Total	0.10

13. STABILITY OF THE OPLE SUPPORT STRUCTURE

The greatest single risk in the support concept is the possibility that ambient disturbances will excite resonant vibrations. The greatest concern is transverse vibrations of the support, which have a first resonance at about 10 Hz. Although tests of inertial block vibrations with an accelerometer (CHARA Technical Report No. 42) showed vibrations above a few Hz were too weak to measure, the T resonance is poorly damped.

If this proves to be a problem, there are several backup options. In case the vibration of the T top with respect to the concrete beam is too great, the crosspiece–sleeper bolts have been installed so that diagonal braces can easily be added to greatly stiffen the joint. If vibration of the entire T with respect to the ground is too great, additional bracing is foreseen to effectively connect the rows of T supports together, probably in two groups of two. These braces would unfortunately block some of the access aisles. This would be an inconvenience, but once the OPLEs are installed and aligned, this would be a tolerable arrangement.

14. EARTHQUAKE DAMAGE

Mt. Wilson is near a number of major faults, and earthquakes must be expected. In mountainous regions (rocky rather than alluvial), the shaking of earthquakes tends to be in the nature of relatively isolated jolts, as opposed to the prolonged shaking often seen in softer ground. An example of the kind of damage which might be expected in a serious but not devastating earthquake on Mt. Wilson may be seen in one of the Mt. Wilson buildings which was damaged during the Northridge quake. The roof of the building, which was not adequately secured to the walls, rose some distance and came down somewhat displaced, but intact.

A likely scenario for the OPLE supports is that the inertia blocks, which were poured in compressed fill rather than bedrock, will rise slightly and settle with different elevations and orientations.

In the event the shaft material used for the OPLE rails is bent, it can be replaced. The purchase price of this shafting was approximately $30,000. As long as the shifts are modest (up to about 1 cm), the sleepers can be adjusted to re-level the supports. If the shifts are up to about 3 cm, it will also be necessary to adjust the crosspieces. The original concept for the composite T design envisioned grouting the crosspiece to concrete beam joint. The possible need for future adjustment is an argument against installing the grout. For the present, the grout will be omitted until the performance of the bolted joint without grout has been adequately evaluated.

15. REFERENCES

Eschbach, W., 1975, *Handbook of Engineering Fundamentals*, Wiley and Sons, New York.
Hool and Pulver, 1937, *Reinforced Concrete Construction: Vol 1*, p. 96.