"CONSTRUCTIBILITY PROBLEMS IN BLAST RESISTANT, REINFORCED CONCRETE STRUCTURES"

by

Darrell D. Barker and Mark G. Whitney
Wilfred Baker Engineering, Inc.
San Antonio, Texas, USA 78209-1128

ABSTRACT

Design of reinforced concrete containment buildings and shelters to resist blast loads is a complex process which involves a great deal of coordination between the engineer and contractor. The high density of reinforcing normally present in these types of structures necessitates close scrutiny by the designer to anticipate fabrication and construction problems. Solutions to these problems are much less expensive to incorporate in the design office than in the field. The problem many designers face is a lack of firsthand information regarding construction techniques for these types of buildings. It is almost impossible to fully appreciate the extent of these problems without observing the actual construction. This paper attempts to point out some the most common problem areas to assist the engineers in evaluating their designs.

Discussion is provided regarding rebar congestion, lacing placement, honeycombing, concrete placement, blast door anchorage, and other problems which frequently occur in construction of blast resistant, reinforced concrete containment bays and shelters. Causes of the problems and suggested solutions are addressed. These discussions will facilitate evaluation of designs by designers, independent reviewers, and sponsoring agencies. This paper reflects the experience of many design professionals involved in blast resistant design and construction obtained through informal surveys.

INTRODUCTION

For many engineers, the primary challenge of designing a blast resistant, reinforced concrete structure is to develop sections capable of resisting the design loads within the allowable response range. Achieving this design at the lowest practical construction cost is also high on the list of priorities. As computational methods become increasingly sophisticated and automated, the ability to determine response with great theoretical accuracy produces a tendency to refine the calculations to an unwarranted degree to achieve the "lowest cost." This approach can produce shallow sections with a high reinforcing ratio which are difficult to construct. Ironically, these are not truly the lowest cost sections in many cases because the cost is measured in terms of material quantities rather than complexity of construction. In practice, a design should be evaluated as much on feasibility of construction as it is on structural performance. Problems with constructibility of the design will always evidence themselves during construction. By contrast, structural response problems may never be discovered since most of these structures are designed for accidental explosions and are never subjected to the design loads. It is prudent, therefore, to examine the potential for construction problems during design and eliminate them prior to bidding the job.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **AUG 1992**	2. REPORT TYPE	3. DATES COVERED **00-00-1992 to 00-00-1992**

4. TITLE AND SUBTITLE **Constructibility Problems in Blast Resistant, Reinforced Concrete Structures**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Wilfred Baker Engineering, Inc.,3330 Oakwell Ct,San Antonio,TX,78209-112**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADA261116, Volume IV. Minutes of the Twenty-Fifth Explosives Safety Seminar Held in Anaheim, CA on 18-20 August 1992.

14. ABSTRACT
see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**11**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

The design of a facility to resist significant blast loads typically produces construction requirements that often do not even resemble those required for conventional loads. This situation is easily understood when the magnitude of the loads involved is considered. Blast pressures as low as a few psi for a long duration are much more demanding of the structure than the most severe natural phenomena loads likely to be encountered by the design engineer.

These unique requirements necessitate a greater attention to constructibility issues during the design phase than would normally be required in conventional construction. The design engineer should also remember that more information concerning fabrication and installation techniques will need to be conveyed to the contractor for blast resistant facilities than for conventional design. The contractor, in many cases, is dealing with a totally new type of construction than he has experienced before. The engineer cannot simply specify a bar size and spacing for each concrete element and leave it to the rebar detailer to iron out the details. If this is done, the chances are good that bar conflicts will require design of new sizes and spacings at construction time when the engineer and contractor can least afford it. Redesign at this stage can also affect adjacent structural elements since most blast resistant facilities involve a system of structural elements rather than individual elements.

This paper describes many of the problems experienced by the authors and several design professionals and construction managers around the country. The problems described are certainly not all encompassing, but they are ones which are encountered frequently. The paper is intended to give the designer with limited experience in this type of construction an indication of what may be encountered and the additional considerations necessary in blast design. The experienced designer will be able to relate to the problems described from personal experience.

IDENTIFICATION OF PROBLEMS

Construction problems associated with this type of facility can be attributed to both design and construction methods. Parties on both sides can be faulted when problems arise, so it is prudent to address factors which are important to both, although this paper is focused on solutions during design. Potential problem areas can be segregated into two broad categories: procedural and technical. Procedural problems involve the way in which design and construction projects are accomplished and include such topics as drawing review and contractual relationships. Technical problems are much narrower in scope and include specific reinforcement and concrete placement issues which can be addressed by designers and contractors.

Procedural Problems

Problems in this category involve procedures, methodologies, and contractual relationships which the design engineer and possibly the contractor have little control over. Consequently, overcoming problems in these areas may be more difficult to solve. The parties involved, however, do have an obligation to influence decisions by owners which can enhance the quality of the completed job.

Constructibility review is a procedural item that is frequently forgotten during design. This review should be an integral part of the design process much like safety and quality assurance reviews have become. Designs should be reviewed not only by the design engineer but also by construction inspection personnel or others with practical construction experience. These reviews should focus on insuring that a reasonable method of construction exists for the specified design. Alternative designs which become apparent at this stage should be considered for adoption if the original design is not feasible. It is not acceptable, as is the practice of some, to simply let the contractor solve the problem. Since this review may impact the design significantly, it should be performed during preliminary design as well as the final stages. An important consideration to remember is that a design is only as good as the constructed product, never better.

The practice of many Architect-Engineers (A-E) is to limit the amount of information on the drawing to reduce their liability should problems arise during construction with a faulty detail or specification. In practice, however, they will still be held responsible if the contractor proves that the design is not constructible. There have been cases where the design was constructible, even though difficult to construct, and blame was still placed on the designer. The moral of the story is make sure you know how to build it and put the necessary information in the construction documents.

It is time consuming, and thus costly, for the A-E to develop detailed reinforcement drawings for particularly congested areas, such as intersecting walls, embeddment areas, and blast door frames. In many cases these costs are not bid into the proposal and there is a tendency to cut this work short when budgets are tight. An important point to remember if this route is taken is that these details must be developed by the contractor and will require review by the A-E. Without guidance from the contract documents, the details may undergo several review cycles before they are correct and thus will cost the A-E just as much as if they had been detailed in the first place. The owner bears some responsibility here also with regard to allowances for additional hours in the A-E's proposal for detailed design of these areas.

Review of shop drawings by the design engineer is another important requirement for this type of work. All of the required reinforcing obviously cannot be "scheduled out" in the contract documents, so the fabricator's detailer must use considerable judgement when preparing the shop drawings. Review of these drawings can be a very tedious job, but its importance should not be forgotten. The design engineer must insure that the intent of the design is incorporated into the shop drawings. The only other chance to review the accuracy of the detailer's work is during a site inspection of the construction. At this point, discovery of errors becomes expensive and unpleasant. The owner has a responsibility in this area also. Review of shop drawings costs money, and tight budgets cause everyone to look for savings. Elimination of reviews, however, can be very costly. Project funding should include provisions for involving the A-E in the construction phase of the project to cover these situations.

On the construction side of the project, a great many problems arise from the inexperience of contractors in this type of work. The contractor must have an experienced superintendent and foreman to plan and oversee reinforcing and concrete placement. Knowledge of proper construction sequence and potential problems is an important asset for the contractor's supervisor to have. An inexperienced supervisor can quickly dissolve the profit margin in this type of facility if reinforcing must be removed and reinstalled because of improper installation.

Government funded projects present a particular problem in this area because of the procurement regulations regarding competitive bidding. It is difficult to exclude contractors with minimal experience from bidding for work even with explicit experience requirements. These requirements are difficult to enforce when protests are filed because they are deemed to be too restrictive. This doesn't mean, however, that there aren't alternatives for getting a good quality facility. One such option is a thorough discussion of the complexity of the job during a prebid conference. This will alert bidders that special attention should be paid to fabrication and labor efforts when preparing their bids. Another important option is the use of an on-site representative of the design team during construction. This representative can help to avoid many of the major problems which occur because of familiarity with the design and the ability to make a quick assessment of the situation. Because he/she has a rather direct line of communication with the other designers, a solution can normally be prepared before the A-E is notified through official channels. This expedites resolution of the problem and saves considerable downtime for the contractor. Since the A-E's representative is normally not the contracting officer, care must be taken to avoid attempting to direct the contractor during resolution of these problems.

Contractor Q-C programs specified by many government contracts warrant special consideration for these projects for two reasons. The first is the availability of personnel with experience in this type of construction. The contract must have specific requirements regarding the qualifications of Q-C personnel. The second is the philosophy of the program itself. To realize the goal of improved quality in the constructed project, the contractor's Q-C personnel must be accountable to the project manager and not controlled by the superintendent or foreman. When reinforcement or concrete placement problems arise in this type of construction, as they frequently do, it is vitally important that they are identified and resolved rather than ignored and forgotten. The consequences associated with this situation should be emphasized to all parties involved.

Technical Problems

Problems in this category involve physical situations which are encountered during construction and thus are more easily recognized than procedural problems. Unfortunately, while these are evident during construction, they are more difficult to recognize during design, and thus may not be resolved before they become expensive. This section will describe some of the more common problem areas and options for minimizing their impact.

Reinforcing

Construction of reinforced concrete elements can be quite complex for blast resistant structures. This is due primarily to the quantity of reinforcing steel in the sections, but is also due to volume of concrete required in confined areas. This congestion stems from requirements placed on the structural elements by the magnitude of the blast loads and space requirements. The presence of lacing, diagonal, and tension bars presents a much greater construction challenge than conventional reinforcing. The size of the flexural steel compared with conventional designs also adds to the congestion. A typical blast resistant structural section is shown in Figure 1.

In many reinforced concrete structures, problems result from an attempt to minimize element thickness by increasing bar sizes and decreasing spacing. This is normally done because it is perceived that the thinnest section is the most economical. While this may be true for conventionally loaded elements, it is not true for most blast designs because of the high cost of rebar placement in congested sections. Increasing element thickness will not increase forming costs, so the only increase is additional concrete and placement cost, and some additional real estate. If space availability is not a problem, use of earth separation between explosives bays to eliminate common walls can result in significant savings in wall construction. These options should be investigated during preliminary design.

As mentioned above, placement of reinforcing steel in sections is the most prominent construction problem in blast resistant structures designed for high pressure loads. The basic types of reinforcing include lacing, stirrups, diagonals, tension, and flexure bars.

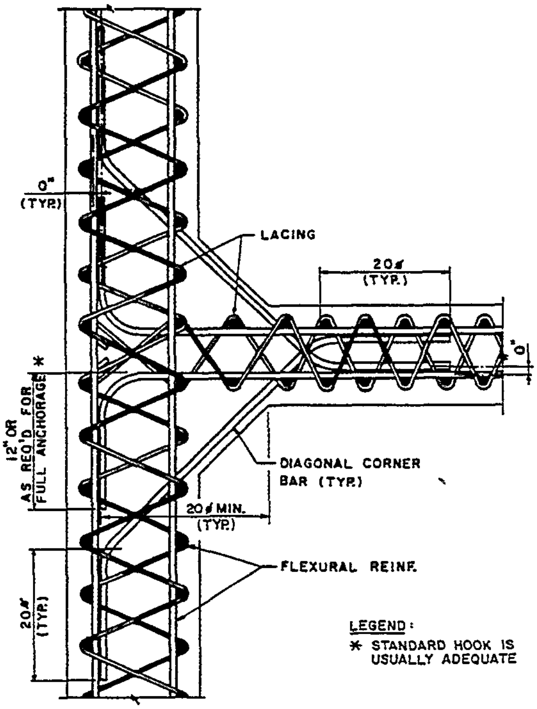

Figure 1. Typical Blast Resistant Structural Section (From TM 5-1300, Ref. 1)

Lacing

Facilities designed for close-in charges require lacing to resist high shear stresses. For sections where lacing is required, it is to be continued through the entire element, not just the region affected by the high shear stresses. This requirement generally necessitates a splice in the lacing at the floor or wall, depending on the height or width. These splices are required to be lapped over three bends (Figure 2), which can make the section very congested, especially where diagonal bars are present. Unfortunately, there isn't a lot of relief from this situation. The best remedies are increasing the bar spacing, using mechanical splices, and lap splicing away from the diagonals. A downside to mechanical splices, however, is the space needed to make the splice, which can be considerable depending on the method selected.

Vertical lacing along the vertical edges of an element makes installation of horizontal diagonal bars extremely difficult. Diagonal bars must be threaded through the lacing, which is physically impossible in some situations. The best solution for this problem is to use horizontal lacing at the vertical edges. These bars can then be placed in layers in conjunction with the diagonal bars.

Normal construction practice for lacing is installation of full height vertical lacing bars along with the vertical flexure bars. Horizontal flexure bars are then added by threading through the bend of the lacing. This becomes a problem when 90° tails are used on the flexure bars. Tails on flexural bars should be eliminated and separate hook bars added after installation to provide anchorage.

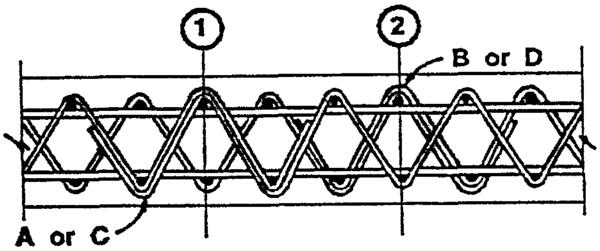

Figure 2. Typical Details for Splicing of Lacing Bars (From TM 5-1300, Ref. 1)

Given the difficulties presented by lacing reinforcement, the best advice is to avoid its use wherever possible. This may include such measures as limiting rotation below 4° to allow use of stirrups, creating appropriate barriers to increase the standoff beyond a scaled distance of 1.0, and increasing section thickness to reduce shear stresses.

Stirrups

Stirrups in conventional construction are fairly common and normally do not present many installation problems. A few additional requirements for blast design purposes, however, make their use more complicated. Where stirrups are required in a section, they must be designed for the critical section and continued through the length of the slab regardless of the actual shear stress in sections away from the support. This requirement is intended to prevent buckling of compression flexure bars. Since stresses above the concrete capacity may exist only for short distances from the support, this requirement adds a significant amount of reinforcing. Another requirement is the use of 135° bends on all hooks, as shown in Figure 3. This makes placement of stirrups after flexural steel very difficult if the reinforcing is very stiff and won't bend enough to loop the stirrup hooks over the bar. In most cases the stirrups must be laid out through the slab and flexural bars threaded through. This is not necessarily difficult, but it can require a significant increase in manpower to install the reinforcing. Another option is to specify a 135° bend on one end and a 90° bend on the other. The 90° bend can then be bent in the field after the stirrup is in place. This option may not be viable, however, if the stirrups are very large.

Diagonals

Diagonal bars are required for slabs in which the actual direct shear exceeds the concrete capacity, support rotations are greater than 2°, or the section is in net tension. In practice, the concrete capacity is usually sufficient, and thus diagonals are normally only necessitated by the latter two requirements. Since internal explosions will produce net tension in most structural elements, diagonals will be quite common in the slabs.

There will always be interference between diagonal bars where orthogonal walls meet because the bars extend into a common element such as a floor or roof slab. There are several remedies for this situation; however, none of these completely eliminates the problem. One approach is to take advantage of the assumed distribution of shear stress on the elements and distribute diagonal steel area based on the 2/3 Vu at the corners as described in Figure 4. This effectively reduces the number of bars at the corners, but doesn't completely eliminate the problem. Another remedy is to adjust the height of the bars in adjacent elements in the field to solve this interference. It

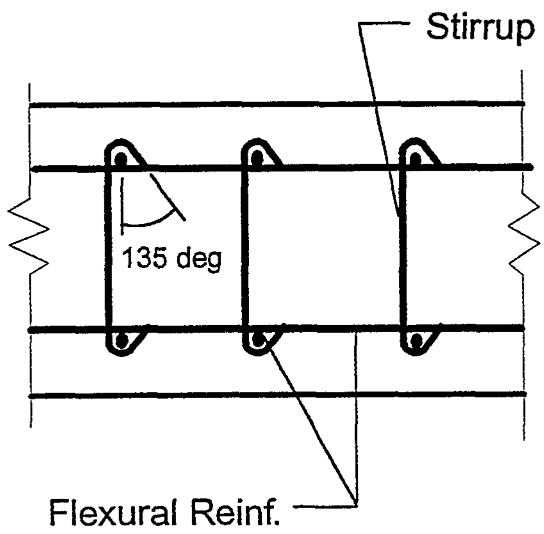

Figure 3. Stirrups for Blast Resistant Sections

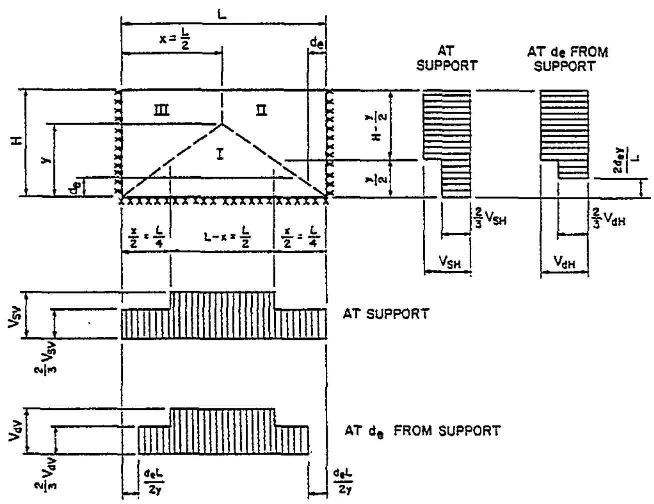

Figure 4. Determination of Ultimate Shears (From TM 5-1300, Ref. 1)

is advisable to address these solutions in the construction drawings. This indicates to the contractor that an interference may occur, and it allows the detailer a chance to design the reinforcing dimensions to facilitate field placement.

The use of haunches in the slab where diagonals are required greatly facilitates the placement of these bars and should be used wherever possible. If it is not possible, the bars will have to be dropped farther into the slab and may interfere with flexure bars.

Tension Bars

These bars are placed in the center of a section to provide a reaction to the shear forces from adjacent elements when the section is in net tension. Because the bars must be anchored at each end of the slab, a hook is normally used. If this hook is integral to the bar, placement of orthogonal lacing becomes very difficult. Use of separate hook bars placed after installation of the tension bars and lacing is suggested. Another solution is to use wall extensions to develop anchorage and eliminate hooks. The spacing of diagonal bars is normally the same as tension steel and many times is detailed to be in the same plane. This interference can be eliminated by staggering the starting point for the tension bars.

Flexure

The most common problem with installation of flexural bars is congestion with the nominal spacing. On paper, a chosen bar spacing can appear to be adequate for installation; however, when actual bar dimensions and fabrication tolerances are considered, the actual free space can be quite small using the out-to-out rebar dimensions. The most obvious solution is use of larger bar spacings. A minimum spacing of 12 in. is suggested to accommodate the various types of reinforcing. A typical section is shown in Figure 5, indicating the various planes of bars required. Calculations of actual free space should be made at the most congested areas. Provision for bending tolerances, even by ACI specifications, can be quite large and must be addressed in the design.

An obvious, yet many times forgotten consideration, is the free space left where adjacent elements intersect. While some bars can remain in the same plane in both elements, many cannot, and thus the nominal spacing must accommodate additional bars. Lap splicing of all the reinforcing, which doubles the number of bars for a particular type, is also a very important consideration for calculation of free space. Use of wall extensions to develop the strength of bars is also an option to minimize the congestion of lap splices at element intersections. A typical section with extensions is shown in Figure 6. The out-to-out dimensions of the reinforcing should be used in the calculations. Although the height of the deformations is relatively small, the total additional space for all the bars can be important.

Interference of flexural bars with other types of reinforcing can be minimized by specifying an offset in the spacing patterns for bars which conflict. This offset should be carefully planned for in the design and should be plainly detailed in the construction documents. It is important that reinforcing be installed as accurately as possible to avoid interference with adjacent slabs. One suggestion to help achieve this is use of temporary structural steel sections in a framework to which the reinforcing is attached. This method has produced excellent results for very heavy reinforcing.

A final suggestion regarding elimination of reinforcing conflicts is the use of three-dimensional graphical or physical models to plan the construction sequence. This step can be very beneficial to the project by facilitating recognition of problems before construction. Problems encountered during construction are almost always much more expensive to remedy than those found during design. The major difficulty here is convincing the owner to pay for this additional work. The necessity of these methods is not readily seen by those unfamiliar with these types of structures, and there may be a reluctance to fund additional design work.

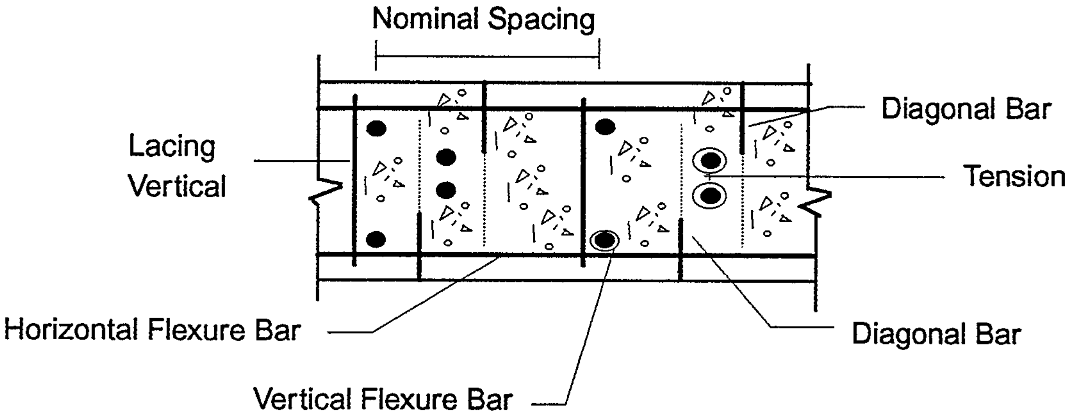

Figure 5. Typical Spacing Pattern
(From TM 5-1300, Ref. 1)

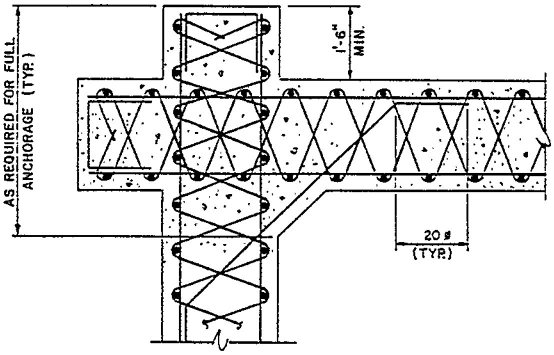

Figure 6. Typical Detail at Corner of Laced Walls
(From TM 5-1300, Ref. 1)

Concrete

The most significant problem with concrete material encountered during construction is proper consolidation. Because of the congestion produced by the reinforcing, flow of the concrete is impeded and voids are left in the section. This result is called honeycombing.

Admixtures

There are several methods of eliminating this problem which are best used together. The first is the use of a high-range water reducer (superplasticizer). This is an additive to the concrete mix which essentially lubricates the cement grains and greatly enhances the flowability of the mix. As the concrete begins to cure, the protective coating around the grains breaks down and the adhesion process begins. Use of these additives can make a low water-cement ratio concrete flow as a liquid without adverse effects on the final cured strength. This is especially beneficial when pumped delivery is used because the concrete loses an inch or two of slump as it travels through hose. Since the concrete behaves more like a liquid when initially poured, the lateral pressures on formwork is greatly increased and must be accounted for in design of the forms.

Placement

Vibration of the concrete is a vital step in assuring a sound cross-section, and strict adherence to proper vibration techniques will eliminate most of the honeycombing problems. Contractors must devote special efforts in teaching these techniques to the operators. With heavy reinforcing congestion, insertion points for the vibrators must be spaced closer together than for conventional sections. The contractor should also be prepared for entanglement of the vibrator head in the reinforcing and provide backup equipment. Use of small diameter heads will help to avoid this problem.

Honeycombing can also be caused by segregation of the coarse aggregate from the cement matrix. This occurs when the concrete mix travels a significant distance through a maze of reinforcing. This can be minimized by use of windows in the formwork. Concrete is placed directly into the wall through the side of the forms with the aid of a concrete pump hose or chute and is deposited closer to its final position without traveling through the rebar. Use of preset steel tremies in the reinforcing is another alternative which works well.

Cover

Generous specifications for concrete cover at the forms and use of smaller coarse aggregate can eliminate many problems associated with honeycombing at the exterior surfaces. Reinforcing which doesn't fit well in the formwork will prevent flow of concrete around the bars and present a void upon removal of the forms. Because much of this reinforcing is relatively large bars, it isn't easy to move the steel away from the forms, and use of a larger cover is well worth the additional cost.

CONCLUSION

Construction of reinforced concrete containment structures and shelters can present some very formidable challenges. The congestion of reinforcing in typical sections requires special considerations by the contractor, but also by the design engineer. Many facilities have been constructed with minimal problems, while others have been plagued with problems which threaten the performance of the structure during a design basis accident.

The design engineer must be aware of these potential problems and adjust the section designs accordingly. It is imperative that sufficient information is included in the drawings to allow the contractor to fabricate and install the reinforcing properly. Attempts to place the burden of resolving all of the constructibility problems on the contractor will ultimately cost the client additional time and money. As most design professionals know, success of the design will be based on the completed structure rather than the contract drawings.

ACKNOWLEDGMENTS

The authors would like to thank the respondents to the constructibility survey for their valuable input during preparation of this paper: in particular, individuals at Booker and Associates, Southwest Research Institute, and Black & Veatch, Engineers-Architects.

REFERENCES

1. "Structures to Resist the Effects of Accidental Explosions" (Revision 1), Army TM 5-1300, Navy NAVFAC P-397, Air Force AFR 88-22, Department of Defense Explosives Safety Board, Alexandria, Virginia, November 1990.