ACI 523.4R-09

Guide for Design and Construction with Autoclaved Aerated Concrete Panels

Reported by ACI Committee 523

American Concrete Institute®

First Printing
June 2009

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Guide for Design and Construction with Autoclaved Aerated Concrete Panels

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Guide for Design and Construction with Autoclaved Aerated Concrete Panels

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This guide is intended for use by architects, engineers, contractors, building officials, and manufacturers. Its purpose is to present, in a single source, information that can help those individuals design, specify, and construct with factory-reinforced panels of autoclaved aerated concrete (AAC). In this guide, introductory information on AAC is first presented, followed by a description of its manufacture, guidance on structural design using reinforced panels, and guidance on construction with such panels. The body of this guide ends with an extensive background chapter on the material characteristics of AAC, and the structural behavior and design of AAC elements.

Keywords: autoclaved aerated concrete; construction; design; panels; reinforced panels.

CONTENTS

ACI 523.4R-09 was adopted and published June 2009.

FOREWORD

This guide is intended for use by architects, engineers, contractors, building officials, and manufacturers. Its purpose is to present, in a single source, information that can help those individuals design, specify and construct with factory-reinforced panels of autoclaved aerated concrete (AAC). In this guide, introductory information on AAC is first presented, followed by a description of its manufacture, guidance on structural design using reinforced panels, and guidance on construction with such panels. The body of this guide ends with an extensive background chapter on the material characteristics of AAC, and the structural behavior and design of AAC elements.

Because design and construction provisions already exist for AAC masonry made from masonry-type units without factory-installed reinforcement, this guide touches only briefly on AAC masonry. This guide addresses design, specification, and construction needs for factory-reinforced panels for which comparable design and construction provisions do not yet exist. It does this through a combination of background material and design guidance, written in nonmandatory format.

This guide is intended as a starting point for the development of mandatory-language design provisions, under the mandate of ACI 318 or other committee so designated by ACI. To facilitate that process, the design provisions proposed in this guide, though written in nonmandatory language as required by ACI, are arranged to follow the format of ACI 318-05.

CHAPTER 1—INTRODUCTION

1.1—Definition of autoclaved aerated concrete

Autoclaved aerated concrete (AAC), a form of cellular concrete, is a low-density cementitious product of calcium silicate hydrates in which the low density is obtained by the formation of macroscopic air bubbles, mainly by chemical reactions within the mass during the liquid or plastic phase. The air bubbles are uniformly distributed and are retained in the matrix on setting, hardening, and subsequent curing with high-pressure steam in an autoclave to produce a homogeneous structure of macroscopic voids, or cells (Fig. 1.1). Material specifications for this product are prescribed in ASTM C1386.

1.2—Typical mechanical and thermal characteristics of AAC

In Table 1.1, typical mechanical and thermal characteristics of AAC are compared with those of conventional concrete, including conventional concrete made with lightweight aggregates. AAC typically has one-sixth to one-third the density of conventional concrete, and about the same ratio of compressive strength, making it suitable for cladding and infill panels and for bearing-wall components of low- to medium-rise structures. Throughout this guide, "density" is defined consistently with ASTM C1386, because AAC is defined by C1386. In C1386, what is referred to as "density" is actually a unit weight, with units of lb/ft^3 (U.S. customary) and units of kgf/m^3 (old metric). This definition is not strictly correct, nor is it consistent with ACI policy for SI units. It is maintained herein for consistency with ASTM C1386.

The thermal conductivity of AAC is 6 to 7.5% that of conventional concrete, making it energy-efficient. Its fire rating is slightly longer than that of conventional concrete of the same thickness, making it useful in applications where fire resistance is important.

AAC has excellent acoustical properties. Because of its characteristic high internal porosity, AAC has very high sound absorption. Because of its lower density, AAC is not as resistant to sound transmission as conventional concrete of the

Fig. 1.1—Macroscopic cellular (void) structure of AAC.

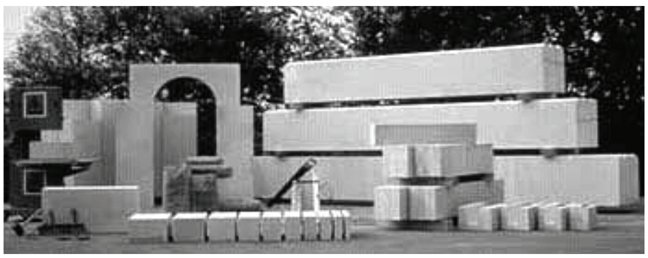

Fig. 1.2—Examples of AAC structural elements.

same thickness. When typical element thicknesses are used, however, AAC has excellent resistance to sound transmission.

1.3—Historical background of AAC

AAC was first produced commercially in Sweden in 1923. Since that time, its production and use have spread to more than 40 countries on all continents, including North America, Central and South America, Europe, the Middle East, the Far East, and Australia. This wide experience has produced many case studies of use in different climates and under different building codes.

In the United States, modern uses of AAC began in 1990 for residential and commercial projects in the southeastern states. United States production of plain and reinforced AAC started in 1995 in the southeast, and has since spread to other parts of the country. A nationwide group of AAC manufacturers was formed in 1998 as the Autoclaved Aerated Concrete Products Association. This guide is an effort by a subcommittee of ACI Committee 523, which includes manufacturers, designers, and researchers, to propose standard design and construction guidelines for reinforced AAC panels.

1.4—Applications of AAC panels

AAC can be used to make unreinforced, masonry-type units, and also factory-reinforced floor panels, roof panels, wall panels, lintels, beams, and other special shapes (Fig. 1.2). These elements can be used in a variety of applications, including residential, commercial, and industrial construction. Reinforced wall panels can be used as cladding systems as well as load-bearing and non-load-bearing exterior and interior wall systems. Reinforced floor and roof panels can be used

Table 1.1—Typical physical characteristics of AAC

Characteristic	AAC	Conventional concrete
Density,* lb/ft^3 (kg/m^3)	25 to 50 (400 to 800)	90 to 150 (1442 to 2400)
Compressive strength f_c, psi (MPa)	290 to 1100 (2.0 to 7.6)	2500 to 8000 (17.2 to 55)
Moisture content after autoclaving	30%	—
Moisture content in use	5 to 15%	—
Coefficient of thermal expansion/°F (/°C)	4.5×10^{-6} (8.1×10^{-6})	5×10^{-6} (9×10^{-6})
Coefficient of creep, per psi (per MPa)	5×10^{-7} (0.72×10^{-4})	2.5×10^{-7} (0.36×10^{-4})
Drying shrinkage (ε_{cs} by ASTM C1386)	$0.8\varepsilon_{cs}/100$	300 to 600 $\mu\varepsilon$
Thermal conductivity, Btu-in./ft^2-h-°F	0.75 to 1.20	10 to 20
Fire rating of 8 in. (200 mm) thick panel, hours (by ASTM E119)	≤ 8	≤ 6

*Throughout this Guide, "density" is defined consistently with ASTM C1386, because AAC is defined by C1386. In C1386, what is referred to as "density" is actually a unit weight, with units of lbf/ft^3 (U.S. customary) and units of kgf/m^3 (old metric). This definition is not strictly correct, nor is it consistent with ACI policy for SI units. It is maintained herein for consistency with ASTM C1386.

efficiently to provide a structure's horizontal diaphragm system while supporting the necessary gravity loads.

1.5—Scope and objectives

This guide is limited to AAC with a density of 50 lb/ft^3 (800 kg/m^3) or less. It is written for structural designers. It addresses design using factory-reinforced AAC panels. Design of AAC masonry is addressed in other documents (Masonry Standards Joint Committee 2005a,b).

Design documents produced by ACI technical committees are classified as standards or nonstandards. The latter include guides, which are intended to present directions for analysis, design, construction, materials, or testing on a general basis. Their language is nonmandatory, permitting the user latitude in judgment concerning particular needs.

The objectives of this guide are to:

- Review the basic characteristics of AAC;
- Provide a brief history of structural applications of AAC;
- Review the fabrication of AAC panels;
- Recommend structural design procedures for factory-reinforced AAC panels; and
- Recommend construction details for use with factory-reinforced AAC panels.

The structural design procedures and construction details recommended in this guide are intended to result in AAC panels with reliable structural capacity, durability, appearance, and overall serviceability.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A = area of wall, in.^{2} (mm^2)

A_s = effective cross-sectional area of horizontal reinforcement in AAC panel, in.^{2} (mm^2)

d = distance from centroid of tension steel to fiber at maximum compressive strain (taken as $0.8\ell_w$ for a shear wall), in. (mm)

d_{cross} = diameter of cross wire (vertical wire) in reinforced AAC panel, in. (mm)
f_{AAC} = tested compressive strength of AAC, psi (MPa)
f'_{AAC} = specified compressive strength of AAC, psi (MPa)
f_{bond} = tensile bond strength of AAC, psi (kPa)
f_c = compressive strength of concrete, psi (MPa)
f_r = modulus of rupture of concrete, psi (kPa)
f_{rAAC} = modulus of rupture of AAC, psi (kPa)
f_s = stress developed in horizontal reinforcement of reinforced AAC panel, psi (MPa)
f_t = splitting tensile strength of concrete, psi (MPa)
f_{tAAC} = splitting tensile strength of AAC, psi (MPa)
f_v = tested shear strength of AAC, psi (MPa)
f_y = specified yield strength of steel reinforcement, psi (MPa)
h = height of shear wall, in. (mm)
h_{crack} = height of flexural crack in a shear wall at flexure-shear cracking, in. (mm)
ℓ_w = plan length of shear wall, in. (mm)
M = moment at the base of shear wall, k-in. (kN-m)
n_{cross} = number of layers of cross wires (vertical) between the failure surface and the closest panel end
P = axial force acting on wall, kips (kN)
S = section modulus, in.^{3} (mm^3)
s_h = spacing of horizontal wires in reinforced AAC panel, in. (mm)
t = specified thickness of shear wall, in. (mm)
V = shear at the base of shear wall, kips (kN)
V_{AAC} = shear strength provided by AAC, kips (kN)
V_c = shear strength provided by concrete, kips (kN)
V_{cr} = base shear at flexural cracking capacity, kips (kN)
V_{ds} = strength of an AAC shear wall as governed by crushing of diagonal strut, kips (kN)
V_n = nominal shear strength of a reinforced concrete section, kips (kN)
V_s = shear strength provided by the shear reinforcement, kips (kN)
V_{ss} = sliding shear capacity of AAC shear wall, kips (kN)
w = horizontal projection of the width of the diagonal strut, in. (mm)
μ = coefficient of friction
ρ = density of AAC

2.2—Definitions

autoclaved aerated concrete (AAC)—a cementitious product based on calcium silicate hydrates in which low density is attained by the inclusion of an agent resulting in macroscopic voids and is subjected to high-pressure steam curing (ASTM C1386).

CHAPTER 3—TYPICAL MATERIALS AND MANUFACTURE OF AAC

3.1—Materials used in AAC

Materials for AAC vary with the method of manufacture and the raw materials available at the location of manufacture, and are specified in ASTM C1386. They include some or all of the following:

- Fine silica sand (ASTM C33, C144, or C332);
- Class F fly ash (ASTM C618) with up to 12% loss on ignition (LOI);
- Hydraulic cements (ASTM C150, C595, or C1157);
- Calcined lime (ASTM C110);
- Gypsum (ASTM C22);
- Expansive agent, such as finely ground aluminum powder or paste;
- Mixing water (clean and free of deleterious substances); and
- Reinforcement (ASTM A82), welded to form cages, with corrosion-inhibiting coating.

3.2—Manufacture of AAC

Overall steps in the manufacture of AAC are shown in Fig. 3.1. Because the same basic AAC material can be used for unreinforced AAC units (masonry-type units) as well as reinforced panels, information on both types of units is presented in this chapter. The masonry-type units are addressed only briefly, for the sake of completeness. Design and construction provisions for AAC masonry units are not addressed by this document. They are addressed by the Masonry Standards Joint Committee (2005a,b).

3.2.1 *Preparation, batching, and mixing of raw materials*—Sand is ground to the required fineness in a ball mill, if necessary, and is stored along with other raw materials. The raw materials are then batched by weight and delivered to the mixer. Measured amounts of water and expansive agent are added to the mixer, and the cementitious slurry is mixed.

3.2.2 *Casting, expansion, and initial hydration*—Steel molds are prepared to receive the fresh AAC. If reinforced AAC panels are to be produced, steel reinforcing cages are secured within the molds. After mixing, the slurry is poured into the molds. The expansive agent creates small, finely dispersed voids in the fresh mixture that increases the volume by approximately 50% in the molds within 3 hours.

3.2.3 *Cutting*—Within a few hours after casting, the initial hydration of cementitious compounds in the AAC gives it sufficient strength to hold its shape and support its own weight. The material is removed from the molds (Fig. 3.2) and fed into a cutting machine that, using wires, sections the blocks and panels into the required sizes and shapes (Fig. 3.3). After cutting, the units remain in their original positions in the larger AAC block.

3.2.4 *Autoclaving*—After cutting, the aerated concrete product is transported to a large autoclave, where the curing process is completed (Fig. 3.4). Autoclaving is required to achieve the desired structural properties and dimensional stability. The process takes about 8 to 12 hours under a pressure of about 174 psi (1.20 MPa) and at a temperature of approximately 360 °F (180 °C), depending on the grade of material produced. During autoclaving, the wire-cut units remain in their original positions in the AAC block. After autoclaving, the individual units are dimensionally stable and are specified to have a drying shrinkage of no more than 0.02% (ASTM C1386). They are then separated for packaging (Fig. 3.5).

3.2.5 *Packaging*—AAC units are normally placed on pallets for shipping. Unreinforced units are typically shrink-

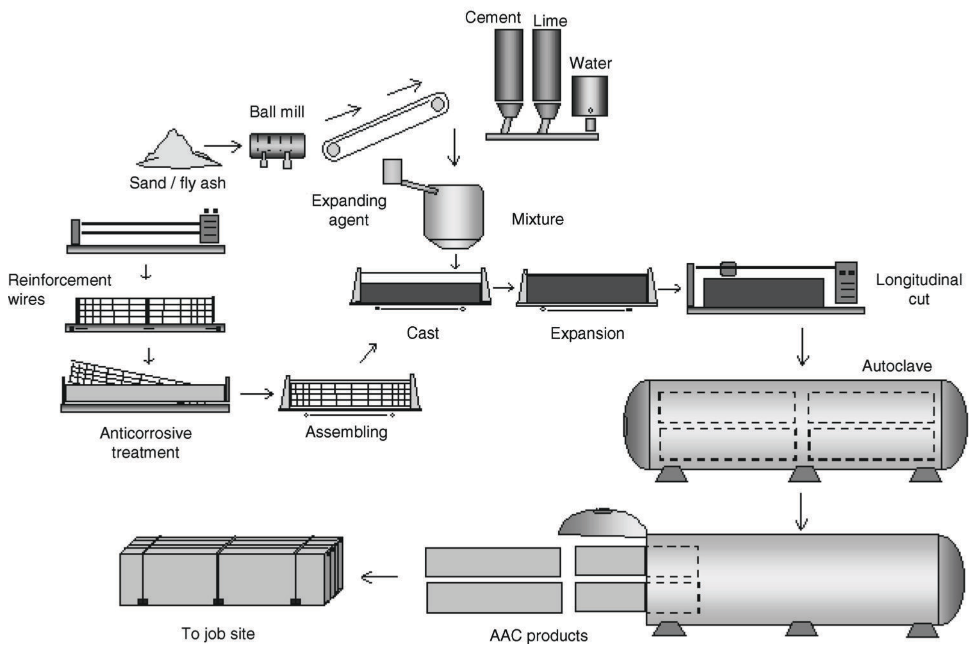

Fig. 3.1—Steps in the manufacture of AAC.

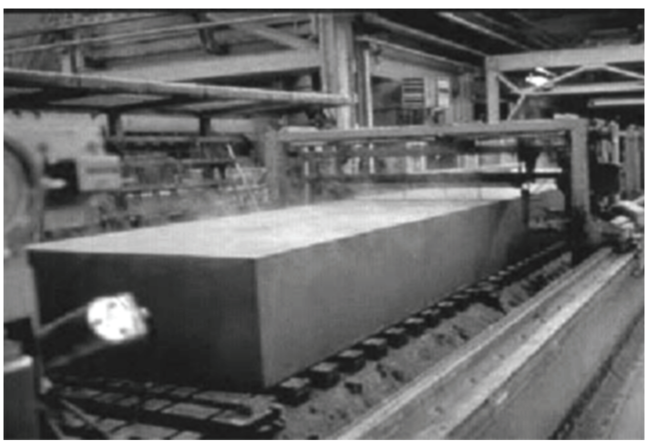

Fig. 3.2—Fresh AAC after removal of molds.

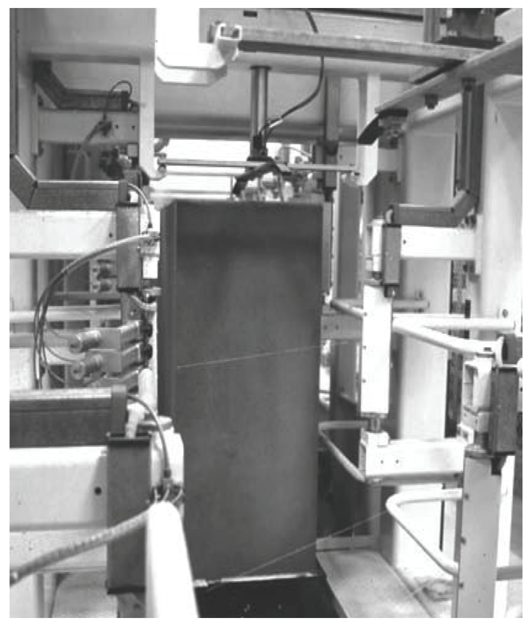

Fig. 3.3—Cutting AAC into desired shapes.

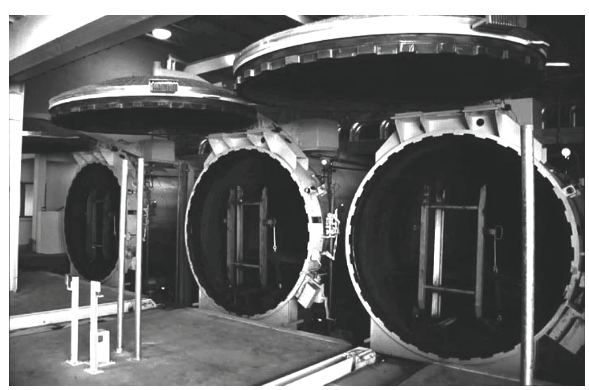

Fig. 3.4—Autoclaving AAC.

wrapped, while reinforced elements are typically banded only, using edge guards to minimize localized damage from the banding.

3.2.6 *AAC strength classes*—AAC is produced in different densities and corresponding compressive strengths in accordance with ASTM C1386 and C1452. Densities and corresponding strengths are described in terms of strength classes. In each case, the strength class corresponds to the specified compressive strength, in psi (MPa) (Table 3.1).

3.3—Typical dimensions of AAC units

3.3.1 *Plain AAC wall units*—Typical dimensions of plain AAC wall units (masonry-type units) are shown in Table 3.2.

3.3.2 *Reinforced AAC panels*—Dimensional tolerances, requirements for reinforcement, and other requirements for reinforced AAC panels are specified in ASTM C1452, which also cites C1386. Typical dimensions for reinforced AAC wall units (panels) are shown in Table 3.3.

Table 3.1—Typical material characteristics of AAC in different strength classes*

Strength class	Specified compressive strength f'_{AAC}, psi (MPa)	Nominal dry bulk density, lb/ft^3 (kg/m^3)	Density limits, lb/ft^3 (kg/m^3)
AAC 2.0	290 (2.0)	25 (400)	22 to 28 (350 to 450)
		31 (500)	28 to 34 (450 to 550)
AAC 4.0	580 (4.0)	31 (500)	28 to 34 (450 to 550)
		37 (600)	34 to 41 (550 to 650)
		44 (700)	41 to 47 (650 to 750)
		50 (800)	47 to 53 (750 to 850)
AAC 6.0	870 (6.0)	44 (700)	41 to 47 (650 to 750)
		50 (800)	47 to 53 (750 to 850)

*Other strength classes within these ranges and densities may be produced depending on specific design requirements.

Table 3.2—Typical dimensions of plain AAC wall units (masonry-type units)

AAC unit type	Width, in. (mm)	Height, in. (mm)	Length, in. (mm)
Standard block	2 to 15 (50 to 375)	8 (200)	24 (610)
Jumbo block	4 to 15 (100 to 375)	16 to 24 (400 to 610)	24 to 40 (610 to 1050)

Fig. 3.5—Packaging of finished AAC units.

3.4—Dimensional tolerances

In accordance with ASTM C1386, dimensional tolerances for plain AAC wall units are ±1/8 in. (±3 mm) in length, thickness, and height. Dimensional tolerances for reinforced elements are given in ASTM C1452, and are listed in Table 3.4.

3.5—Identification and marking of AAC units

Pallets of unreinforced AAC units should be labeled with strength class, production identification code, and size of units. Reinforced AAC panels should bear product identification information indicating the strength class, production identification code, and a number indicating the specified location in the structure.

Table 3.3—Typical dimensions of reinforced AAC wall units (panels)

Product type	Thickness, in. (mm)	Height or width, in. (mm)	Typical length, ft (mm)
Wall panel	2 to 15 (50 to 375)	24 (610)	20 (6090)
Floor panel	4 to 15 (100 to 375)	24 (610)	20 (6090)
Lintel/beam	4 to 15 (100 to 375)	8 to 24 (200 to 610)	20 (6090)

Table 3.4—Dimensional tolerances for reinforced AAC panels (ASTM C1452)

Dimension	Floor or roof panels, in. (mm)	Wall panels, in. (mm)
Length	±0.20 (±5)	±0.20 (±5)
Width	±0.12 (±3)	±0.12 (±3)
Thickness	±0.12 (±3)	±0.12 (±3)
Tongue	±0.12 (±3)	±0.12 (±3)
Groove	±0.12 (±3)	±0.12 (±3)

CHAPTER 4—STRUCTURAL DESIGN OF REINFORCED AAC PANELS

4.1—Introductory remarks regarding design provisions

This document is a guide. Its design provisions are nonmandatory, and are a synthesis of design recommendations from the Autoclaved Aerated Concrete Products Association, and from the results of research conducted at the University of Alabama at Birmingham (UAB), the University of Texas at Austin (UT Austin), and elsewhere.

In this chapter, the proposed design provisions are briefly introduced in narrative form. In Chapter 5, handling and erection of panels are addressed. In Chapter 6, typical design details are used to introduce the reader to specific configurations of the AAC structural elements whose design and construction are addressed by this document. Chapter 7 presents the detailed technical justification for the proposed design provisions. The proposed provisions themselves and corresponding commentary are presented in Appendixes A and B, respectively. Appendix C provides design examples.

The specific design provisions of Appendix A, and their associated commentary in Appendix B, are written in nonmandatory language. They are intended to be compatible in organization, numbering, and form with the design provisions of ACI 318 to facilitate their use by concrete designers and also to facilitate their future consideration, in mandatory form, by ACI Committee 318. For that reason, the provisions are arranged to refer directly to ACI 318-05. Additions and exceptions are specifically noted. New subcategories are inserted for new design provisions.

Loads for structural design of AAC panels should be taken from appropriate standards, such as ASCE 7. Strength-reduction factors (ϕ-factors) for AAC panels depend on the actions under consideration. They reflect the statistical variability of the capacity, and the accuracy of the capacity-calculation formulas. When failure is governed by yield and fracture of tensile reinforcement, ϕ-factors are justifiably identical to those used for reinforced concrete. When failure is governed by crushing or diagonal tension of the AAC itself, ϕ-factors are similar to those used for the design of conventional concrete. They may even be higher, because the

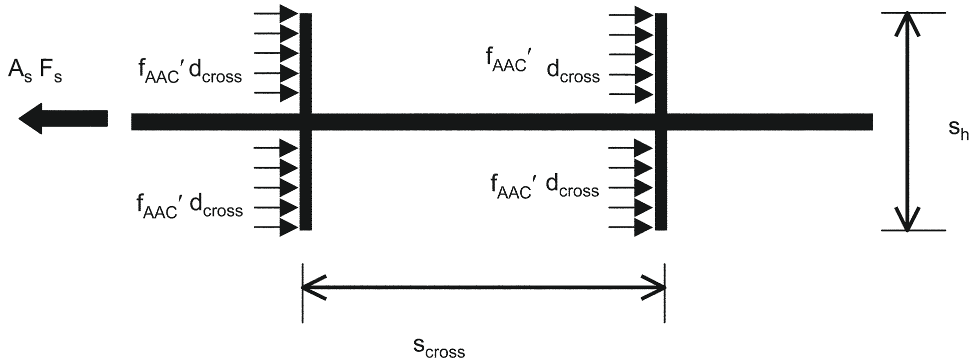

Fig. 4.1—Bond mechanism of steel wire cages in AAC (Tanner 2003).

factory production of AAC leads to decreased variability in its mechanical characteristics compared with conventional concrete.

The design provisions of this guide are not intended for use with unreinforced, masonry-type units. Design of those units is covered by the Masonry Standards Joint Committee (2005a,b).

4.2—Proposed design provisions for reinforced AAC panels

4.2.1 *Basic design assumptions*—The proposed design provisions for reinforced AAC panels are based on the same principles used for strength design of conventional reinforced concrete elements: strain compatibility between AAC and reinforcement (with some modifications as noted); stress-strain behavior of AAC and reinforcement; and equilibrium. The design strength of AAC in compression is based on a specified design compressive strength f'_{AAC}. Compliance with that specified compressive strength is verified by compressive strength testing of AAC cubes, using ASTM C1386, when the AAC panels are fabricated. The design strength of AAC in tension is proposed as a function of the specified compressive strength. The design strength of reinforcement in tension is proposed as the specified yield strength.

4.2.2 *Combinations of flexure and axial load*—AAC panels are designed for combinations of flexure and axial load using principles identical to those for conventional reinforced concrete. Nominal capacity is computed assuming plane sections; strain in tensile reinforcement depends on whether the section is tension- or compression-controlled; the stress in compressive reinforcement is computed based on its strain and its stress-strain behavior; and the distribution of compressive stress in the AAC is approximated by an equivalent rectangular stress block, whose height is $0.85f'_{AAC}$ and whose value of β_1 is 0.67 (Tanner et al. 2005a,b; Argudo 2003). For the complete flexure and axial load behavior, an interaction diagram can be constructed using the principles described previously for various levels of axial load.

Because reinforced AAC panels usually have equal areas of tensile and compressive reinforcement, flexural capacity is usually tension-controlled (in the terminology of ACI 318-05). The stress in the compressive reinforcement is often neglected in computation of nominal capacity. Sections are under-reinforced (in the terminology of ACI 318-99). As compression steel is added to a beam, the neutral axis shifts toward the extreme compression fiber. Because the compressive strain in the top fiber is fixed, the strain in the extreme tensile steel increases. By using equal compression and tension steel, the neutral axis shifts to a distance less than two times the clear cover, provided that the compressive stress block accounts for 30% of the total compressive force. This results in a strain in the tensile reinforcement of 0.003 × ([d – 2(cover)]/[2(cover)]). As long as the ratio of ([d – 2(cover)]/[2(cover)]) exceeds 1.67 × (0.005/0.003), the section will be tension-controlled as defined in ACI 318-05. For a reinforced panel with a depth of 8 in. (200 mm) and cover of 1 in. (25 mm), this ratio is 2.5, which is greater than 1.67. If the panel depth increases, this ratio increases further.

4.2.3 *Bond and development of reinforcement*—Reinforcement in AAC panels consists of steel wire cages installed when the panels are produced, and deformed reinforcement installed in 3 to 4 in. (75 to 100 mm) grouted cores as the panels are erected.

Bond and development requirements for deformed reinforcement in grout are identical to those used for concrete or masonry construction. Given the small sizes of deformed bars used in AAC construction, bond between the grout and the AAC itself does not govern the bond capacity (Tanner et al. 2005a,b).

Bond and development requirements for steel wire cages embedded in AAC are quite different from those for conventional concrete. Because the steel wire cage has a corrosion-resistant coating, the bond strength between the coated wire and the AAC itself is negligible. Bond strength comes from bearing of the cross wires against the AAC. For typical cross-wire spacings (s_{cross} in Fig. 4.1), local crushing of the AAC under the cross wires can be assumed to redistribute the bearing stresses under the cross wires, leading to a uniform bearing strength of f'_{AAC} under every cross wire. The stresses are initially greater at the weld due to increased stiffness at this location. Weld strength should meet the requirements of ASTM C1452. After local deformations occur at the weld, the more flexible portion of the wires is assumed to resist a uniformly distributed load. Multiplying this stress by the number of cross wires and by the bearing area of each cross wire gives the maximum force that can be developed in the steel wire cage (Fig. 4.1). The conservative design assumption is to neglect the contribution of welded-