FIRST DRAFT

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American National Standard

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FOREWORD

Introduction

In September 2023 the ICC Board of Directors, responding to the lack of a consensus industry standard that establishes material specifications for *3D printing material*, structural design standards for 3D printing walls, and wall-to-floor connections, appointed a consensus committee to develop a standard.

Development

This is the first edition of the International Code Council® (ICC®) 1150 Automated Construction Technology for 3D Printing Walls Standard. It is partly based on the ICC Evaluation Service, LLC (ICC-ES) Acceptance Criteria for Automated Construction Technology for 3D Printing Walls (AC509). This standard was developed by the ICC 3D Automated Construction Technology Consensus Committee (IS-3DACT) that operates under ANSI-approved ICC Consensus Procedures for the development of ICC standards.

The meetings of the IS-3DACT Consensus Committee were open to the public and interested individuals and organizations from across the country and globe participated. Views and objections were solicited through several public comment periods. All views and objections were considered by the consensus committee and an effort was made toward their resolution. A vote by the consensus committee approved this standard.

The requirements in ICC 1150—202X are based on the intent to expand and update the established technical requirements of ICC-ES AC509 and provide requirements of AC509 into a mandatory language format that removes commentary, ambiguity and product certification requirements which are not appropriate for a consensus standard. It also improves upon the technical requirements to reflect current industry practices related to materials testing and structural design. A task group specifically reviewed the provisions within the standard to eliminate any conflicts with codes and establish common terms and rigor. The resulting document provides appropriate protections for health, safety and welfare while avoiding unnecessary restrictions on the use of new materials, technologies or designs.

Adoption

ICC 1150 Automated Construction Technology for 3D Printing Walls Standard is available for reference and use by jurisdictions in both codes and incentive programs internationally. It represents an advancement of the performance and installation requirements in AC509 and it is appropriate for use as an adoptable successor to AC509. Its use within a governmental jurisdiction is intended to be accomplished through adoption by reference in accordance with proceedings establishing the jurisdiction's law.

Interpretations

Requests for interpretations on the provisions of ICC 1150—202X should be addressed to: ICC, Central Regional Office, 4051 Flossmoor Road, Country Club Hills, IL 60478.

Interpretations

All ICC standards are revised as required by ANSI. Proposals for revising this edition are welcome. Please visit the ICC website at www.iccsafe.org for the official "Call for Proposals" announcement. A proposal form and instructions can also be downloaded from www.iccsafe.org. ICC, its members, and those participating in the development of ICC 1150—202X do not accept any liability resulting from compliance or noncompliance with the provisions of ICC 1150—202X. ICC does not have the power or authority to police or enforce compliance with the contents of this standard. Only the governmental body that enacts this standard into law has such authority.

FOREWORD

International Code Council 3D Automated Construction Technology Standard Consensus Committee (IS-3DACT)

Consensus Committee SCOPE: The 3D Automated Construction Technology Standard Consensus Committee (IS-3DACT) shall have primary responsibility for minimum requirements to safeguard the public health, safety and general welfare along with minimum performance, and evaluation requirements for automated construction technology for 3D printing walls. The requirements contained in the International Codes pertaining to these situations shall be coordinated with the standards developed by the IS-3DACT Consensus Committee.

This standard was processed and approved for submittal to ANSI by the ICC 3D Automated Construction Technology Standard Consensus Committee (IS-3DACT). Committee approval of the standard does not necessarily imply that all committee members voted for its approval. Representatives on the Consensus Committee are classified in one of three voting interest categories, General Interest (G), User Interest (U) and Producer Interest (P). The committee has been formed in order to achieve consensus as required by ANSI Essential Requirements. At the time it approved this standard, the IS-3DACT Consensus Committee consisted of the following members:

David Langefeld (P), ICON Technology, Inc., Austin, TX

Gabriel Carrera, P.E. (U), Wiss, Janney, Elstner, Austin, TX

Bora Gencturk, Ph.D., P.E. (U), University of Southern California, Los Angeles, CA

Rory Hamaoka, CBO, MCP, S.E. (G), Lawrence Berkeley Lab, Richmond, CA

Werner Hellmer, PE, CBO, FACI (G), Clark County Building Department, Las Vegas, NV

Maryam Hojati (U) University of New Mexico, Albuquerque, NM

Berok Khoshnevis (U), Contour Crafting Corporation, El Segundo, CA

Eric Kreiger (P), Army Corps of Engineers, Champagne, IL

Doug Mayer, P.E., S.E. (G), California Department of Health Care Access and Information, Fresno, CA

Paul Messplay, MCP, CBO, CFM (G), Virginia Department of Housing and Community Development - State Building Codes Office, Mechanicsville, VA

Adil Tamimi (U), American University of Sharjah College of Engineering, Sharjah, UAE Sharjah, United Arab Emirates

Bing Tian, Ph.D. (P), The Quikrete Companies, Johns Creek, GA

Co-Secretariat: **Melissa Sanchez, S.E. LEED AP**, ICC-ES Principal Structural Engineer, Brea, California.

Co-Secretariat: **Aileen Vandenberg, Ph.D.**, ICC-ES Evaluation Specialist, Brea, California.

Voting Membership in Each Category

Category	Number
General (G)	4
User (U)	5
Producer (P)	3
TOTAL	12

Interest Categories

General Interest: Individuals assigned to the General Interest category are those who represent the interests of an entity, including an association of such entities, representing the general public, or entities that promulgate or enforce the provisions within the committee scope. These entities include consumers and government regulatory agencies.

User Interest: Individuals assigned to the User Interest category are those who represent the interests of an entity, including an association of such entities, which is subject to the provisions or voluntarily utilizes provisions within the committee scope. These entities include academia, applied research laboratory, building owner, design professional, government nonregulatory agency, insurance company, private inspection agency and product certification/evaluation agency.

Producer Interest: Individuals assigned to the Producer Interest category are those who represent the interests of an entity, including an association of such entities, which produces, installs, or maintains a product, assembly or system subject to the provisions within the committee scope. These entities include builder, contractor, distributor, laborer, manufacturer, material association, standards promulgator, testing laboratory and utility.

NOTE—Multiple Interests: Individuals representing entities in more than one of the above interest categories, one of which is a Producer Interest, are assigned to the Producer Interest.

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CHAPTER 1

APPLICATION AND ADMINISTRATION

SECTION 101 PURPOSE

101.1 Purpose. The purpose of this standard is to establish design provisions for *3D printed walls* and their connections where the walls are built using 3D *automated construction technology* (3D-ACT) with proprietary or non-proprietary *3D printing materials*, that are in compliance with the intent of the model building codes.

SECTION 102 SCOPE

102.1 Scope. This standard applies to *3D automated construction technology* and *3D printing materials* used to construct interior and exterior *3D printed walls*, with or without structural steel reinforcing, used as bearing walls, non-load bearing walls, and shear walls, in one-story or multi-story structures. The walls are to be constructed by printing (extruding) the *3D printing material* in layers to create wall configurations including, but not limited to, a wall with two printed outer face shells with a *core fill grout* poured between the shells to form a solid wall, a wall with two printed outer face shells and composite action achieved through a printed web and/or reinforcement, and multiple shell walls with shells without integral cores that are considered veneer, where the out-of-plane load is transferred to a structural shell.

This standard also provides specifications for *3D printing materials*, and structural design standards for *3D printed walls* and wall-to-floor connections. *3D printed walls* used as the lateral-force-resisting system are limited to Seismic Design Categories (SDC) A and B.

SECTION 103 COMPLIANCE ALTERNATIVES

103.1 Compliance alternatives. Nothing in this standard is intended to prevent the use of designs, products or technologies as alternatives to those prescribed by this standard, where equivalence is provided, and such equivalence is approved by the administrative authority adopting this standard.

SECTION 104 TESTING LABORATORIES AND REPORTS

104.1 Testing Laboratories and Reports. The testing agency used for the laboratory tests specified in this chapter shall meet the requirements of ASTM E329 and be accredited in accordance with the requirements of ASTM C1077. All laboratory testing for evaluating the *3D printing materials* shall be carried out by certified testing laboratories or institutes. The results of testing shall be reported in accordance with ISO/IEC Standard 17025 Section 5.10.

SECTION 105 SPECIAL INSPECTION

105.1 Special Inspection. Special inspection shall be provided in accordance with Sections 1705.1.1 and 1705.3 of the IBC during the mixing, printing, and placing of the *3D printing material* shells and *core fill grout*. The inspection shall include verification that the concrete compressive strength is in compliance with the minimum compressive strength specified in the construction documents.

SECTION 106 STRUCTURAL OBSERVATION

106.1 Structural Observation. No structural observation is mandated by this standard unless such observation is required by the registered design professional responsible for the structural design, or such observation is specifically required by the code official.

SECTION 107 LISTING AND LABELING

107.1 Listing and Labeling. The *3D automated construction technology* and packaging of *3D printing materials* shall be listed and labeled denoting compliance with this standard.

SECTION 108 MINIMUM INFORMATION REQUIRED IN CONSTRUCTION DOCUMENTS

108.1 General. The following information that are specific to *3D automated construction* shall be included in the construction documents: a general description of the 3D printing system used including the nozzle dimensions, the design method utilized either in conformance with Section 404 or Section 406 of this standard, the weight of the structure considered, nominal bead dimensions (width and height), an indication of whether dimensionally controlled or non-dimensionally controlled extrusion is used, material design strengths and reporting age for cementitious materials, print stop interlayer protocols (where applicable), and maximum aggregate size used in *3D printing material*. All other requirements related to construction documents from IBC shall still apply.

SECTION 109 REFERENCED DOCUMENTS

109.1 Referenced documents. The codes and standards referenced in this standard shall be considered part of the requirements of this standard to the prescribed extent of each such reference. Chapter 6 contains a complete list of all referenced standards. Use of the most recent edition of the standards referenced in Chapter 6 is assumed unless the standard year is referenced in the applicable building code. This standard references sections of the 2024 International Codes; section numbers from earlier versions are noted in parentheses where different.

CHAPTER 2

DEFINITIONS

SECTION 201 GENERAL

201.1 General. For the purpose of this standard, the terms listed in Section 202 have the indicated meaning.

201.2 Undefined Terms. The meaning of terms not specifically defined in this document or in referenced standards shall have ordinarily accepted meanings such as the context implies.

201.3 Interchangeability. Words, terms, and phrases used in the singular include the plural and the plural include the singular.

SECTION 202 DEFINED TERMS

2-COMPONENT (2K) 3D PRINTING MATERIAL. Proprietary or non-proprietary *3D printing material* containing a base and optionally an admixture package for being used at the jobsite. The base is composed of cement, fine/coarse *aggregates*, and, if applicable, *supplementary cementitious materials*, and if applicable, short discontinuous *fibers*. The optional admixture package contains one or multiple *admixtures* to regulate setting time, freeze-thaw resistance, and/or workability, among others. A specific dosing mechanism is used in the printer/mixer system to inject the *admixtures* and homogenously mix the *3D printing material*.

3D AUTOMATED CONSTRUCTION TECHNOLOGY (3D-ACT). Construction-scale 3D printing technology, also known as additive manufacturing or layer-by-layer automated construction technology, used in the construction of buildings, or building components, consisting of a computer program (*3D printer software*) and computer-controlled equipment (*3D printer*) to create three-dimensional shapes with 3D printing material.

3D PRINTING WALLS. Walls constructed with the use of *3D automated construction technology* using 3D printing material. Walls may be printed in various configurations, including but not limited to, printing 3D printing material in layers to create two outer face shells with a *core fill grout* between the shells to form a solid wall. If applicable, structural steel reinforcing shall be placed within the *core fill grout*, or within the shell layers.

3D PRINTER. Computer-controlled equipment, which includes batching, mixing, and delivery systems used to support and control the position and orientation of a nozzle, used to construct 3D printed walls.

3D PRINTER SOFTWARE. The computer program used to control the 3D printing material flow and nozzle speed, position, and orientation, among others.

3D PRINTING CONCRETE: A proprietary or non-proprietary cementitious 3D printing material with coarse *aggregates*.

3D PRINTING MATERIALS. A proprietary or non-proprietary cementitious material (concrete or mortar) that consists of cement, *fibers* (if applicable), *supplementary cementitious materials* (if applicable), fine and/or coarse aggregate, and *admixtures* (if applicable). *3D printing material* is extruded in layers during construction.

3D PRINTING MATERIAL MIX DESIGN. Proprietary or non-proprietary *3D printing material design* specifying the proportioning of ingredients for *3D printing materials* usually in weight or volume fractions.

3D PRINTING MORTAR. A proprietary cementitious *3D printing material* with fine *aggregates* and no coarse *aggregates*.

ADMIXTURES. A liquid, or dispersible powder, used as an ingredient in a cementitious mixture to improve its economy and/or properties in the plastic and/or hardened state.

AGGREGATES. Granular material, such as sand, gravel, and crushed stone, used with a cementing medium to produce either concrete or mortar.

CEMENT. Any hydraulic cementitious material that is capable of binding aggregate particles together.

CORE FILL GROUT. Cementitious grout poured in place between the 3D printed shells. The *core fill grout* is either the same as, or a different mixture than, the *3D printing material*. The *core fill grout* could be mixed in place, supplied by ready mix plants, or be pre-packaged product.

DIMENSIONALLY CONTROLLED EXTRUSION. Bead, shell, or both with a cross section that has been formed, shaped, or both using physical means on both sides after extrusion but before setting to conform it to a given shape, profile, or smoothness.

FIBERS. A slender and elongated solid material, generally with a length at least 100 times its diameter.

FIELD MIX 3D PRINTING MATERIAL. *3D printing material* mixture (mortar or concrete) being batched, mixed, and used at jobsite.

NON-DIMENSIONALLY CONTROLLED EXTRUSION. Bead, shell, or both with an as-extruded cross section that has had no physical intervention to conform it to a given shape, profile, or smoothness.

PRE-PACKAGED 3D PRINTING MATERIAL. Pre-packaged proprietary or non-proprietary *3D printing material* containing *cement*, fine/coarse *aggregates*, and, if applicable, *supplementary cementitious materials*, and if applicable, short discontinuous *fibers*, and if applicable *admixtures*. The pre-packaged *3D printing materials* may contain multiple *admixtures* to regulate setting time, freeze-thaw resistance, and/or workability.

SUPPLEMENTARY CEMENTITIOUS MATERIALS. Inorganic materials such as fly ash, silica fume, metakaolin, or slag *cement* that reacts pozzolanically or hydraulically.

WATER/MIXING WATER. The water in freshly mixed cementitious mixtures, exclusive of any previously absorbed by the aggregate (batched water).

SECTION 203 NOTATION

A_1 = the loaded area but not greater than the bearing plate or bearing cross-sectional area, in.^{2}

A_2 = the area of the lower base of the largest frustrum of a right pyramid that has the area A_1

A_{br} = bearing area, in.^{2}

A_{cv} = gross area of concrete section bounded by web thickness and length of section in the direction of shear force considered in the case of walls. Gross area is total area of the defined section minus area of any openings, in.^{2}

A_g = gross area of concrete section, in.^{2}

A_s = area of longitudinal reinforcement located at least 2/3 of the overall element depth away from the extreme compression fiber, in.^{2}

A_{vf} = area of shear-friction reinforcement, in.^{2}

b = width of compression face of member, in.

b_w = web width or diameter of circular section, in.

d = distance from extreme compression fiber to centroid of longitudinal tension reinforcement, in.

d_b = diameter of deformed bar/wire, in.

E_c = design modulus of elasticity of *3D printing materials,* psi

E_g = design modulus of elasticity of *core grout fill,* psi

E_s = design modulus of elasticity of reinforcement materials, psi

f_c' = design compressive strength of *3D printing materials,* psi

f_g' = design compressive strength of *core grout fill,* psi

f_y = design yield strength of reinforcement materials, psi

h = effective structural contact width, in.

h_{eff} = equivalent wall thickness, in.

k = effective length factor for wall

l = span length of beam or one-way slab; clear projection of cantilever, in.

l_c = the height of the wall, ft.

l_d = development length of straight deformed bar and wire, in.

l_{dh} = development length of hooked deformed bar and wire, in.

l_n Clear height of core, in.

M_{cr} = nominal cracking moment, in.-lb

M_n = nominal flexural strength at section, in.-lb

N = number of beads within a shell
P_n = nominal axial capacity, lb

S_m = elastic section modulus, in.^{3}

s_w = clear spacing of cores, in.

V_n = nominal shear strength at section, lb

w_c = design unit weight of *3D printing materials*

ε_{ty} = yield strain of reinforcement materials

ϕ = strength reduction factor

ϕ_{3D} = 3D strength reduction factor

ρ = ratio of A_s to shear area

CHAPTER 3

3D PRINTING MATERIAL LABORATORY PREQUALIFICATION - TESTING METHODS AND PERFORMANCE REQUIREMENTS

SECTION 301 TESTING SUBMITTAL AND MATERIAL MIXING

301.1 Material mixture constituents. Cementing materials shall conform to ASTM C150/C150M, ASTM C595/C595M, or ASTM C1157/C1157M. *Aggregates* shall conform to ASTM C33/C33M or ASTM C144. *Admixtures* shall conform to ASTM C260/C260M, ASTM C494/C494M, or ASTM D98. Steel *fibers* shall be deformed and conform to ASTM A820/A820M. Glass *fibers* shall conform to ASTM C1666/C1666M. Synthetic *fibers* shall conform to ASTM D7508/D7508M. Natural *fibers* shall conform to ASTM D7357. Fly ash or natural pozzolans such as metakaolin shall conform to ASTM C618. Silica fume shall conform to ASTM C1240. Slag *cement* shall conform to ASTM C989/C989M. *Mixing water* for *3D printing material* shall comply with ASTM C1602/C1602M.

301.2 Testing submittal. For *3D printing material* mixed from individual ingredients, the manufacturer shall submit mixing instructions to the testing agency. In the case of *2-component (2k) 3D printing material*, the base material, the additive package, the suggested dosage, and time of addition of the additive shall be submitted. The mixture design must specify the dosage range, delivery waiting time (if applicable), and mixing time required for the mixture component to yield the desired performance. In the case of *pre-packaged 3D printing materials*, the final product shall be submitted for testing along with mixing proportions. For all *3D printing materials*, the same mixing procedure shall apply to both laboratory prequalification tests mentioned in Section 302 and the actual field use of the materials.

301.3 Material mixing and curing. For qualification or acceptance of the *3D printing material*, the environmental conditions of the mixing room and curing water shall meet ASTM C511. All the raw materials listed in the mixture design including the *mixing water* shall be conditioned to room temperature before mixing. Mixing of *3D printing concretes* shall be performed according to ASTM C192/C192M, while mixing of *3D printing mortars* shall be performed according to ASTM C305. In the case of *pre-packaged 3D printing material*, the requirements of mixing and water content listed on the product technical datasheet (TDS) should be followed. The *3D printing materials* shall be cured in the laboratory according to ASTM C192/C192M prior to testing in accordance with Section 303.

301.3.1 Material mixture deviations. Depending on the nature and complexity of the mixture design, deviations from the mixing methods described in ASTM C192/C192M and ASTM C305 may be required to achieve the desired fresh properties, particularly if chemical *admixtures* are used. These deviations shall be clearly called out in the material mixing instructions provided by the manufacturer. The method, time, and sequence of addition of chemical *admixtures* as well as any other deviations from the standard test methods must be reported.

SECTION 302 FRESHLY MIXED 3D PRINTING MATERIAL TESTING METHODS

302.1 General. The fresh properties of *3D printing materials* shall be measured in accordance with Sections 302.1 through 302.5 using the same test methods unless explicitly indicated otherwise. Workability, air content, density and set time tests shall start within five minutes of finalizing the mixing sequence.

302.2 Workability. The workability of the freshly mixed *3D printing material* shall be determined in accordance with ASTM C1437 for *3D printing mortar* and in accordance with ASTM C143/C143M for *3D printing concrete*.

302.3 Air content. The air content of the freshly mixed *3D printing material* shall be determined in accordance with ASTM C231/C231M.

302.4 Density (unit weight). The density of *3D printing concrete* shall be determined in accordance with ASTM C138/C138M. The density of *3D printing mortar* shall be measured in accordance with ASTM C185.

302.5 Set time. When a specific set time is required for material performance, the initial and final set times for *3D printing concrete* shall be measured in accordance with ASTM C403/C403M and the initial and final set times for *3D* *printing mortar* shall be measured in accordance with ASTM C807 for mortar and wet sieved concrete. In case of rapidly setting *3D printing materials*, the time interval for needle drops shall be modified and modifications shall be reported by the testing agency.

SECTION 303 HARDENED 3D PRINTING MATERIAL TESTING METHODS AND PERFORMANCE SPECIFICATIONS

303.1 General. The *3D printing material* shall be prepared and cured in accordance with Section 301.3. The hardened properties shall be evaluated in accordance with Sections 303.2 through 303.4.

303.2 Compressive strength. The compressive strength for *3D printing mortar* shall be conducted on 2 in. (50 mm) cube specimens in accordance with ASTM C109/C109M. The compressive strength for *3D printing concrete* shall be conducted on 3 in. by 6 in.(75 mm by 150 mm) cylinder specimens in accordance with ASTM C39/C39M.

303.3 Shrinkage. The drying shrinkage of the *3D printing materials* shall be evaluated in accordance with ASTM C157/C157M. Acceptable length change values for *3D printing materials* after 28-days of air storage shall be less than 0.10% (1,000 microstrains).

303.4 Interior wall finish test. If synthetic *fibers* are used in *3D printing materials* for interior wall finish, a specimen of the *3D printing material*, with the maximum thickness (up to 4 in. [100 mm]) and maximum synthetic fiber dosage, shall be tested in accordance with ASTM E84 or UL 723. Interior wall finishes shall have a flame spread index of 25 or less and a smoke development index of 450 or less.

SECTION 304 LONG TERM DURABILITY TESTING METHODS AND PERFORMANCE SPECIFICATIONS

304.1 Freezing and thawing resistance. In regions where freeze-thaw resistance is required by the authority having jurisdiction, the resistance of the *3D printing material* shall be determined in accordance with ASTM C666/C666M Method A for a minimum of 300 cycles. The average durability factor shall be a minimum of 80.

304.2 Alkali silica reaction. The susceptibility of *aggregates* to alkali-silica reaction (ASR) shall be evaluated according to and be in compliance with ASTM C1260.

304.3 Chloride exposure requirements. The durability of ACI CODE-318 Section 19.3 shall apply.

CHAPTER 4

STRUCTURAL DESIGN

SECTION 401 GENERAL DESIGN REQUIREMENTS

401.1 General. The provisions of this chapter provide minimum load, resistance, and prescriptive requirements for structures within the scope of this standard to safeguard against major structural failures and loss of life. These provisions establish minimum requirements, and this standard does not address all design considerations. The registered design professional shall be responsible for the complete design of the 3D-ACT wall systems, including design considerations not specified herein.

401.2 Design Approach. The design and detailing of structural elements of 3D-ACT wall systems, including their connections to other structural elements, shall comply with one of the following methodologies.

401.2.1 Engineered Design. The structural design of conventionally reinforced, planar 3D-ACT wall systems shall comply with the minimum detailing requirements of Section 403, the engineering requirements of Section 404 and, where applicable, the connection requirements of Section 405.

401.2.2 Structural Testing. It shall be permitted to determine the structural design of 3D-ACT wall systems through alternative testing requirements of Section 406. Wall systems shall meet the minimum detailing requirements of Section 403 and the connection requirements of Section 405 unless structural testing is performed showing that an alternative method provides equal or better performance than the minimum requirements outlined in Sections 403 and 405.

401.3 Construction Systems. The provisions of this chapter govern the construction of 3D-ACT wall systems. Materials used in the construction shall conform to Chapter 3.

401.3.1 Building Configuration. The requirements of this standard are based on a balloon framing system, where the walls are continuous from the foundation to the roof. Other framing systems must have equivalent detailing to ensure force transfer, continuity, and compatible deformations.

401.3.2 Wall Composition. The 3D-ACT wall systems shall consist of one or more shells of *3D printing materials* complying with the minimum reinforcement requirements in Section 403, with regularly spaced cores printed integrally with the shells. Cores shall be reinforced and filled with *3D printing material*, concrete, or grout.

401.3.2.1 Integral Cores. The printed beads of integral cores shall have effective side face contact with the adjacent shell(s), determined in accordance with Section 404.3.2. Cores and shells shall be connected using cross-ties in accordance with Section 403.4. Cores in 3D-ACT wall systems are analogous to cores in concrete masonry unit construction and shall not refer to vertical elements such as pilasters and columns which contain longitudinal reinforcement and ties.

401.3.2.2. Webbing. Webbing is defined as printed extrusions between multiple shells. Webbing shall utilize effective side face contact to provide connection from webbing to shells. Examples of webbing are shown in Figure 401.3.2.2.

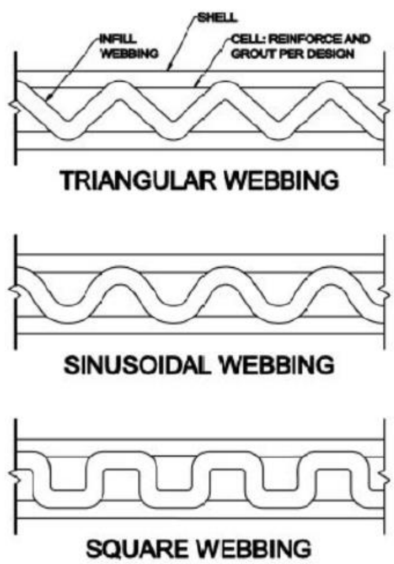


FIGURE 401.3.2.2. WEBBING EXAMPLES

401.3.2.3 Non-Load Bearing Walls. Non-load bearing walls are permitted to be designed without integral cores provided the top of the wall is laterally supported or stability of the wall can be demonstrated through a rational analysis.

401.3.3 Wall Classifications. The 3D-ACT wall systems shall be classified and designed as follows.

401.3.3.1 Single-Shell Walls. Single-shell wall sections with integral cores shall be permitted. The shell shall be assumed to act as a horizontal one-way flexural element designed to transmit out-of-plane loads to cores. Cores shall be designed to transmit out-of-plane loads to the foundation. The cross-section consisting of the shell and cores shall be assumed to act as axial elements designed to transmit gravity loads to the foundation.

401.3.3.2 Multi-Shell Walls. Multi-shell walls with or without integral cores shall be permitted.

Shells without integral cores shall be considered a veneer, where out-of-plane load is transferred to structural shell(s) through a means of connection as described in Section 403.5. Shells without integral cores shall have no axial load-carrying capacity.

Shells with integral cores shall be assumed to act as horizontal one-way flexural elements designed to transmit out-of-plane loads to cores. Cores shall be designed to transmit out-of-plane loads to the foundation. The cross section consisting of shells and integral cores shall be assumed to act as axial elements designed to transmit gravity loads to the foundation.

401.3.4 Composite Action. Considerations for composite action of multi-bead shells and multi-shell 3D-ACT wall systems shall be in accordance with this section.

401.3.4.1 Multi-Bead Shells. Multi-bead shells in 3D-ACT wall systems shall be classified as non-composite unless the beads have effective side face contact, as determined in Section 404.3.2, and minimum cross ties are provided in accordance with Section 403.6. When multi-bead shells do not include cross ties but have effective side face contact, the inter-bead shear stresses shall not exceed 80 psi (550 kPa).

401.3.4.2 Multi-Shell Walls. Multi-shell walls shall be classified as non-composite unless a rational analysis is provided to verify that cross ties and webbing are adequate to transfer between shells the horizontal shear stresses developed from the design loads being considered.

401.3.5 Stay-in-Place Formwork. Where 3D-ACT wall systems are used as stay-in-place formwork such that the cavity is filled with one or a combination of conventionally reinforced concrete walls, pilasters, or columns, design of the 3D-ACT wall system for use as formwork shall follow ACI PRC-347. Minimum reinforcement shall be provided in accordance with Section 403. Infill concrete elements, such as walls, pilaster, and columns, shall be designed in accordance with ACI CODE-318.

401.4 Continuous Load Path. A continuous load path, or paths, with adequate strength and stiffness shall be provided to transfer all vertical and lateral loads from the roof, wall, and floor systems from the point of application to the supporting structural elements.

401.5 Foundations. Foundation systems supporting structures with 3D-ACT wall systems shall be designed in accordance with the building code adopted by the administrative authority adopting this standard as applicable for the intended use of the structure. Connection of the 3D-ACT wall systems to the foundation shall be in accordance with Section 405 of this standard.

401.6 Floor Systems. Floor systems supported by 3D-ACT wall systems shall be designed in accordance with the appropriate sections of the building code adopted by the administrative authority adopting this standard as applicable for the intended use of the structure. Connection of the 3D-ACT wall systems to the floor systems shall be in accordance with Section 405 of this standard.

401.7 Roof Systems. Roof systems supported by 3D-ACT wall systems shall be designed in accordance with the appropriate sections of the building code adopted by the administrative authority adopting this standard as applicable for the intended use of the structure. Connection of the 3D-ACT wall systems to the roof systems shall be in accordance with Section 405 of this standard.

401.8 Structural Analysis. A first-order elastic analysis that satisfies equilibrium using the original undeformed geometry of the structure shall be permitted; however, the effects of slenderness, including both the individual member slenderness and the structure's deflections, shall be considered.

SECTION 402 DESIGN CRITERIA

402.1 Design Loads. Structural elements of 3D-ACT wall systems shall be capable of resisting the design loads given in the building code adopting this standard. In addition to the specified design loads, the following provisions apply specifically to 3D-ACT wall systems.

402.1.1 Self-Weight Dead Loads. The self-weight dead load used in the structural design of the 3D-ACT wall system, foundation, and other supporting elements shall be based on the actual weight of the 3D-ACT wall system. Self-weight dead load shall be based on the nominal shell width, including any material printed in place but not contributing to the structural capacity of the wall system.

402.1.2 Uplift Resistance. The self-weight dead load for resisting uplift forces shall be based on the effective structural contact width of the 3D-ACT wall system. Excess material printed and in place but not contributing to the structural capacity of the wall system shall not be included.

402.2 Load Combinations. Load combinations applied to structures containing 3D-ACT wall systems shall be in accordance with the building code adopting this standard.

402.3 Design Strength. Structural design of 3D-ACT wall systems in accordance with this standard shall follow Load and Resistance Factor Design (LRFD). Structural elements shall be designed such that their design strength equals or exceeds the demand calculated using the load combinations referenced in Section 402.2. Design strength shall be the nominal strength multiplied by the strength-reduction factors specified in Section 404.12 or the design strength determined in accordance with Section 406.

402.4 Seismic Design Criteria. 3D-ACT wall systems used as the lateral force resisting system are limited to SDC A and B unless additional testing and analysis beyond the scope of this standard is performed and approved by the administrative authority adopting this standard.

SECTION 403 DETAILING REQUIREMENTS

403.1 General. Minimum detailing requirements for 3D-ACT wall systems shall be provided in accordance with Section 403.

403.2 Minimum Vertical Reinforcement. Minimum vertical reinforcement for 3D-ACT wall systems shall consist of one #4 bar or larger in each integral core with integral cores spaced no further than 75 percent of the vertical span of the wall. An integral core containing one #4 bar or larger shall be located within 8 in. (200 mm) of the ends of walls.

403.3 Minimum Horizontal Reinforcement. Minimum horizontal reinforcement for 3D-ACT wall system shells shall be in accordance with Table 403.3.1. The bar or wire diameter in printed beads shall be limited to 30 percent of the effective structural contact width. For splice locations, the bar diameter shall be the equivalent diameter of the bars being spliced. Horizontal reinforcement spacing for structural shells shall not exceed the lesser of $3 \times h_{eff}$, as defined in Section 404.3.5 or 18 in. (450 mm). Horizontal reinforcement spacing for veneer shells shall not exceed 12 in. (300 mm). Reinforcement shall be placed at mid-width of the shell.

Table 403.3.1
Shell Minimum Horizontal Reinforcement

Type of Reinforcement	f_y, (psi)	Minimum Reinforcement Ratio
Bars	60,000	0.0020
	< 60,000	0.0025
Wire	Any	0.0020

403.4 Minimum Connections Between Cores and Shells. Integral cores shall be connected to the shell or shells in accordance with this section.

403.4.1 Single-Shell Walls. Integral cores shall be connected to the shell by means of a cross tie(s) with two legs that encapsulates the core area and vertical reinforcement. Core cross-ties shall consist of a minimum wire diameter of W2.8 (3/16 in. [4.8 mm]) and shall be spaced at a distance not to exceed 12 in. (300 mm) on-center. Cross-ties may be omitted if a rational analysis shows that the horizontal shear demands between the core and the shell is less than 80 psi (550 kPa).

403.4.2 Multi-Shell Walls. Integral cores shall be connected to the shell by means of a cross tie with one leg. The core cross-ties shall consist of a minimum wire diameter of W2.8 (3/16 in. [4.8 mm]) and shall be spaced not more than 18 in. (450 mm) on-center. Cross-ties connecting multiple shells as described in Section 403.5 fulfill this requirement. Cross ties shall not be required if a rational analysis shows that the horizontal shear demands between the core and the shell is less than 80 psi (550 kPa).

403.5 Minimum Connections Between Shells. Multi-shell 3D-ACT wall systems shall contain minimum cross-ties connecting the shells in accordance with this section. For cavity widths not exceeding 4 in. (100 mm),cross ties shall consist of a minimum wire diameter of W1.7 (0.148 in. [3.76 mm]) spaced not more than 16 in. (400 mm) on-center in both directions. For cavity widths greater than 4 in. (100 mm) but not exceeding 6 in. (150 mm), cross ties shall consist of a minimum diameter of W2.8 (3/16 in.[4.8 mm]) spaced not more than 16 in. (400 mm) on-center in both directions. Other cavity widths and cross tie configurations may be used if verified by a detailed tie analysis or structural testing considering both positive and negative design pressures.

403.6 Minimum Connections Between Beads in Multi-Bead Shells. Where the shell consists of multiple beads that are assumed to be composite, cross ties consisting of 0.01 sq. in. per sq. ft. (69.4 sq. mm per sq. m) of wall area shall connect the two beads.

403.7 Minimum Concrete Cover. Minimum concrete cover for reinforcement in 3D-ACT wall systems shall comply with Table 403.7.1.

Table 403.7.1 Minimum Concrete Cover for Reinforcement*

Exposure Condition	Reinforcement Type	Cover, in.
Exposed to weather or in contact with ground	No. 6 and larger	2
	No. 5 and smaller	1-1/2
	Cross Ties and Horizontal Reinforcement	5/8**
Not exposed to weather or in contact with ground	All Bar Sizes	3/4
	Cross Ties and Horizontal Reinforcement	1/2**

Notes:
* Alternative methods of protecting the reinforcement from weather may be provided if they are equivalent to the additional concrete cover required by this standard.
** Reinforcement shall be fully embedded in *3D printing materials* and shall be protected from corrosion by using stainless steel or a hot-dipped galvanized coating or epoxy coating. If the above corrosion protection requirements are not met, minimum concrete cover shall be the same as for other reinforcement. Reinforcement material specifications shall comply with Section 404.2.3.

403.8 Minimum Core Fill Dimensions. For a core fill placement height of 12 ft. (3.7 m) or less, with a maximum aggregate size of 1/2 in. (12.7 mm), the minimum core fill area shall be 9 sq. in. (5800 sq. mm), and the minimum clear dimension shall be 2-1/2 in (64 mm). Where a larger maximum aggregate size is used, minimum clear dimensions shall be in accordance with ACI CODE-318, Section 25.2.1. Splices shall be considered when determining the minimum clear dimensions.

Fill heights exceeding 12 ft. (3.7 m) and fill dimensions smaller than those specified above are permitted if the results of a core fill demonstration show that the cores are filled and adequately consolidated. In that case, the procedures used in constructing the core fill demonstration shall be the minimum acceptable standard for core filling, and the quality assurance program shall include inspection during construction to verify core fill placement.

403.9 Reinforcement in Cores, Headers, and Bond Beams. Reinforcement embedded in cores, headers, and bond beams shall have a clear distance between the reinforcement and beads not less than 1/2 in. (12.7 mm) for *3D printing mortar*. For *3D printing concrete*, clear distance shall conform to ACI CODE-318, Section 25.2.1. The diameter of reinforcement shall not exceed one-third the least dimension of the gross infill space in which it is placed, and the area of reinforcement shall not exceed 4 percent of the gross infill space. Where lap splices are included, the area of reinforcement shall not exceed 8 percent of the gross infill space.

403.10 Bond Beams. 3D-ACT wall systems shall have a continuous bond beam or equivalent element at each story of the wall to transfer concentrated loads and diaphragm forces to the wall.

403.11 Structural Integrity. For multi-story 3D-ACT wall systems, the size of vertical integrity ties shall not be at least the equivalent of one #4 bar spaced at 8 ft. (2.4 m) on-center or 75 percent of the vertical span of the wall, whichever is less, and shall be continuous over the full height of the building. Vertical integrity ties shall be fully developed in the foundation.

403.12 Corners and Wall Intersections. Unless separated by an expansion joint, walls that intersect shall be designed to provide lateral support for one another or from infill elements within those walls. The joints and connections shall be designed and detailed to allow vertical and in-plane deformation of the supported wall without restraint. Cores shall be located within 6 in. (150 mm) of corners and wall intersections.

403.13 Parapets. Unreinforced solid parapet walls that are part of 3D-ACT wall systems shall not be less than 8 in. (200 mm) thick, and their heights shall not exceed four times their thickness. Unreinforced, hollow parapet walls shall have an h_{eff} of at least 8 in. (200 mm)and their height shall not exceed 3×h_{eff}. Parapet walls in areas subject to wind loads of 30 pounds per square foot (1.4 kPa) or more shall be reinforced.

403.14 Joints. Joints shall be provided at regular intervals to reduce cracking due to restrained volume change in accordance with this section.

403.14.1 Expansion/Contraction Joints. Contraction joints shall be spaced at a minimum of 25 ft. (7.6 m) on-center and within 15 ft. (4.6 m) of a wall corner. Horizontal reinforcement shall be discontinuous at joint locations. Reinforcement detailing around joints shall ensure structural integrity of the shells.

403.14.2 Print Stops. Print stops are horizontal discontinuities created by stopping and then starting printing. The maximum start-stop time between extrusion layers defining a print stop shall be specified in the construction documents. The print stop interlayer protocol such as the application of a bonding agent or other surface preparation techniques shall be specified in the construction documents.

SECTION 404 STRUCTURAL WALL DESIGN PROVISIONS

404.1 General. This section provides minimum design requirements for 3D-ACT wall systems used for structural and non-structural walls, as part of the vertical-force-resisting system, lateral-force-resisting system, or both, in single- or multi-story structures. These provisions shall be limited to conventionally reinforced, planar wall systems.

404.2 Material Properties. Material properties assumed for the structural design of 3D-ACT wall systems shall conform to the provisions of this section.

404.2.1 3D Printing Materials. Structural properties of the *3D printing materials* shall be established in accordance with Chapter 5 and shall meet the requirements of this section.

404.2.1.1 Unit Weight. The design unit weight, w_c, of *3D printing materials* shall be as follows unless a different value is established through testing of hardened *3D printing materials*.

$w_c = 145\ pcf$ for *3D printing concrete*

$w_c = 125\ pcf$ for *3D printing mortar*

404.2.1.2 Compressive Strength. The design compressive strength, f_c', shall be at least 2,500 psi (17.2 MPa) but no greater than 8,000 psi (55 MPa).

404.2.1.3 Modulus of Elasticity. The design modulus of elasticity, E_c, shall be calculated as follows unless a different value is established through testing of hardened *3D printing materials* in accordance with ASTM C469/C469M.

$E_c = 500 f_c'$, where f_c' has units of psi, for *3D printing mortar*

$E_c = 900 f_c'$, where f_c' has units of psi, for *3D printing concrete*

404.2.1.4 Inter-Layer Bond Strength. The design inter-layer bond strength, shown in Figure 404.2.1.4, shall be taken as 75 psi (520 kPa).

404.2.1.5 Inter-Bead Shear Strength. The design inter-bead shear strength, shown in Figure 404.2.1.4, shall be taken as 80 psi (550 kPa) where the beads are in direct contact but do not contain cross ties per Section 403.5.

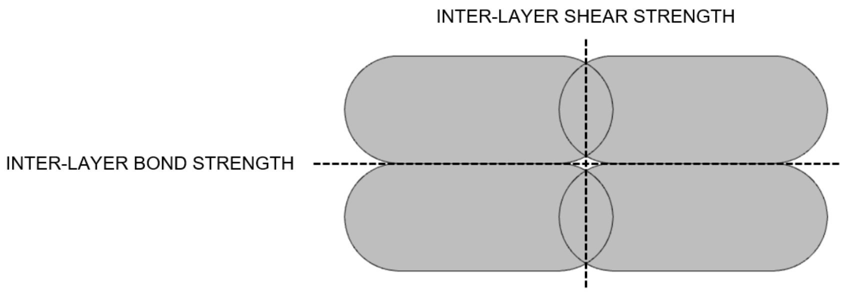


FIGURE 404.2.1.4 INTER-LAYER BOND STRENGTH AND INTER-BEAD SHEAR STRENGTH IN MULTI-BEAD SHELLS

404.2.2 Core, Header, and Bond Beam Fill Material. Fill grout and concrete material shall conform to ASTM C476 and ASTM C94/C94M, respectively. If *3D printing materials* are used for fill, they shall conform to Chapter 3 of this standard.

404.2.2.1 Compressive Strength. The design compressive strength, f_g', shall be at least that of the *3D printing material* but not more than 8,000 psi (55 MPa).

404.2.2.2 Modulus of Elasticity. The design modulus of elasticity, E_g, shall be calculated as follows unless a different value is established through testing. For concrete, the modulus of elasticity shall be in accordance with ACI CODE-318.

$E_g = 500f_g'$, where f_g' has units of psi, for *3D printing mortar*

$E_g = 900f_g'$, where f_g' has units of psi, for *3D printing concrete*

404.2.3 Reinforcement. Reinforcement materials for 3D-ACT wall systems shall be in accordance with this section and, unless specified otherwise, shall comply with Table 404.2.3.1.

Table 404.2.3.1 Reinforcement ASTM Material Specifications

Deformed Bars	Uncoated: A615, A706, A996, A955 Coated: A767, A775, A934, A1055
Deformed and Plain Wire	Uncoated: A1064, A1022 Coated: A951, A641, A884

404.2.3.1 Stress-Strain Relationship. The design stress-strain relationship of deformed reinforcement shall be assumed as a bilinear curve in both tension and compression.

404.2.3.2 Yield Strength. The design yield strength, f_y, of deformed bars shall be based on the specified grade of reinforcement and shall not exceed 60,000 psi (410 MPa). The design yield strength, f_y, of wires shall be based on the specified grade of reinforcement and shall not exceed 75,000 psi (520 MPa).

404.2.3.3 Modulus of Elasticity. The design modulus of elasticity, E_s, shall be permitted to be taken as 29,000,000 psi (200 GPa).

404.2.3.4 Yield Strain. The yield strain, ε_{ty}, shall be equal to f_y/E_s. For Grade 60 deformed reinforcement, it shall be permitted to be taken equal to 0.002.

404.3 Section Properties. Structural design of 3D-ACT wall systems shall be based on the section properties determined in accordance with this section.

404.3.1 Effective Structural Contact Width. The effective structural contact width between multiple beads of 3D-ACT wall systems shall be as defined in Figure 404.3.1. The effective structural contact width is a function of the nominal bead width. Design may be performed using the presumptive effective structural contact width in Section 404.3.1.1 or the measured effective structural contact width as defined in Section 404.3.1.2. Where the print path includes offsets of one bead relative to the one below it for creating textured walls, the effective structural contact width shall account for the said offset.

404.3.1.1 Presumptive Values. In the absence of published effective structural contact width based on measurements, the following may be used to determine the effective structural contact width based on the nominal bead width. If the nominal bead width is not given or defined, the designer shall assume and justify a nominal bead width.

404.3.1.1.1 Single-Bead Shells. The effective structural contact width between layers of a single-bead shell shall be taken as:

1. 70 percent of the nominal bead width for *non-dimensionally controlled extrusions*.
2. 90 percent of the nominal bead width for *dimensionally controlled extrusions*.

404.3.1.1.2 Multi-Bead Shells. The effective structural contact width between layers of a multi-bead shell shall be taken as:

1. The nominal bead width multiplied by $\left(0.7 + 0.85(N-1)\right)$ for *non-dimensionally controlled extrusions*, where N is the number of beads within the shell.
2. The nominal bead width multiplied by $\left(0.9 + 0.95(N-1)\right)$ for *dimensionally controlled extrusions*, where N is the number of beads within the shell.

404.3.1.2 Tested Values. The effective structural contact width shall be determined by measurements of printed test specimens defined in Section 501. Printed test specimens shall be representative of the bead and shell geometry being designed, including bead height, extrusion shape, dimensional control, and print path overlap for multiple beads. Measurements of the effective structural contact width from the sawn and exposed cross-sections of the shell, shown in Figure 404.3.1, shall be performed with a caliper calibrated according to ASME B89.1.14. A minimum of 15 measurements of different interfaces on both the single- and double-beads shall be performed. The effective structural contact width for both the single- and double-bead shall be reported as 2.33 standard deviations below the mean measured width.

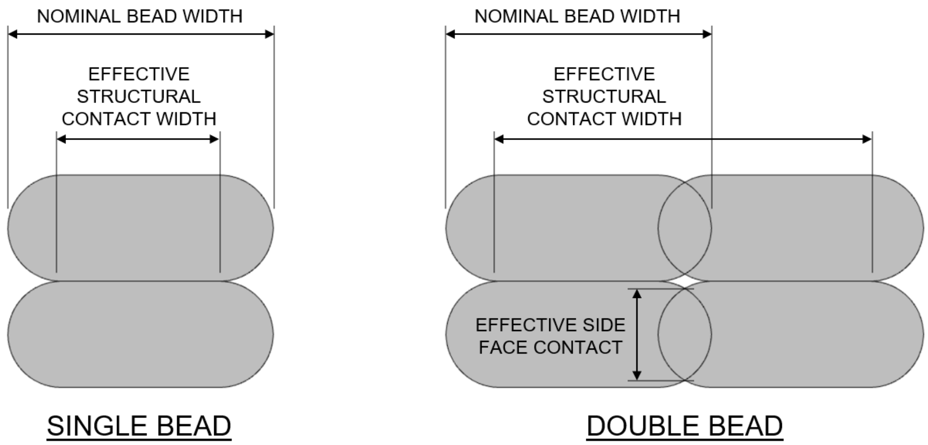


FIGURE 404.3.1. EFFECTIVE STRUCTURAL CONTACT WIDTH FOR SINGLE-BEAD AND MULTI-BEAD SHELLS (*NON-DIMENSIONALLY CONTROLLED EXTRUSIONS* SHOWN)

404.3.2 Effective Side Face Contact. The effective side face contact between multiple beads of 3D-ACT wall systems, as would occur where multiple beads make up a single shell, where integral cores contact the shell, and where webbing contacts the shells, shall be as defined in Figure 404.3.1. Integral cores and webbing are required to have effective side face contact. Refer to Sections 401.3.2.1 and 401.3.2.2. Design may be based on presumptive values in Section 404.3.2.1 or measured values as defined in Section 404.3.2.2.

404.3.2.1 Presumptive Values. In the absence of published effective structural contact width based on measurements, effective side face contact shall be assumed if the ratio of the single-bead and double-bead effective structural contact widths is greater than or equal to the following:

1. $0.7/\big(0.7 + 0.85(N-1)\big)$ for *non-dimensionally controlled extrusions*, where N is the number of beads within the shell.
2. $0.9/\big(0.9 + 0.95(N-1)\big)$ for *dimensionally controlled extrusions*, where N is the number of beads within the shell.

404.3.2.2 Tested Values. The effective side face contact shall be verified by measurements of printed test specimens defined in Section 501. Printed test specimens shall be representative of the bead and shell geometry being designed, including bead height, extrusion shape, dimensional control, and print path overlap for multiple beads. Measurements of the effective side face contact from the sawn and exposed cross section of the shell, shown in Figure 404.3.1, shall be performed with a caliper calibrated according to ASME B89.1.14. A minimum of 15 measurements of different interfaces shall be performed. The effective structural side face contact shall be reported as 2.33 standard deviations below the mean. Effective side face contact requires at least 85 percent of the nominal bead height to be in contact.

404.3.3 Area. Members shall be designed for axial strength using section properties based on a design cross-sectional area determined from the effective structural contact width of the member or portion thereof under consideration.

404.3.4 Flexural Moment of Inertia. Deflection calculations for unreinforced elements shall be based on uncracked, gross section properties. Deflection calculations for reinforced elements shall be based on cracked section properties. Where multiple materials of differing stiffnesses makeup the cross section, the lower stiffness material shall be assumed to make up the entire section. Alternatively, transformed section properties may be used. The flexural stiffness properties assumed for deflection calculations shall not exceed one-half of the gross section properties, unless a cracked-section analysis is performed.

404.3.5 Equivalent Wall Thickness. The equivalent wall thickness, h_{eff}, for axial strength shall be computed such that the uncracked out-of-plane moment of inertia of the 3D-ACT wall system is equal to the uncracked moment of inertia of a solid wall having a thickness of h_{eff}.

404.4 Out-of-Plane Loads. 3D-ACT wall systems shall be designed for out-of-plane loads in accordance with this section.

404.4.1 Effective Flange Width. For analysis of integral cores, the effective width of the shell(s) is permitted to be considered in the calculation of the flexural capacity of the core. The effective shell width of the section shall be in accordance with Table 404.4.1. Effective shell width shall not be taken larger than the core spacing.

Table 404.4.1 Effective Shell Width

Flange Location	Effective Overhanging of Flange Width beyond Face of Core	
Each Side of Core	Least of:	$8h$
		$s_w/2$
		$l_n/8$
One Side of Core	Least of:	$6h$
		$s_w/2$
		$l_n/12$

Notes:
h = effective structural contact width (in.)
s_w = clear spacing of cores (in.)
l_n = clear height of core (in.)
1 in. = 25.4 mm

404.4.2 Shear and Flexural Capacity. The shear and flexural capacity of shells and cores shall be determined in accordance with this section. Differing capacities for positive and negative pressures shall be considered. Connections between the cores and the foundation, and between the cores and the diaphragms shall be designed in accordance with Section 405.

404.4.2.1 Span. Shells shall be assumed to be simply supported between vertical elements for out-of-plane flexural loads. Multi-span analysis of the shells shall not be permitted.

404.4.2.2 Plain or Reinforced Concrete. Cores shall be reinforced in accordance with Section 403.2. Where multi-bead shells are composite, the shell shall be considered reinforced if its structural depth, d, is at least 2 in. (50 mm) and horizontal reinforcement is provided in accordance with Section 403.3. Where multi-bead shells are non-composite, the individual beads shall be considered reinforced if an individual bead's structural depth, d, is at least 2 in. (50 mm) and horizontal reinforcement is provided in accordance with Section 403.3. Other cases shall be considered unreinforced.

404.4.2.3 Unreinforced Flexural Capacity. The nominal flexural capacity shall be the lesser of:

$$M_n = 5\sqrt{f'_c}S_m \text{ and } 0.85f'_cS_m \quad \text{(ACI CODE-318 Equations 14.5.2.1a and b)}$$

404.4.2.4 Unreinforced Shear Capacity. The nominal shear capacity shall be equal to:

$$V_n = \frac{4}{3}\sqrt{f'_c}b_wh \quad \text{(ACI CODE-318, Table 14.5.5.1)}$$

404.4.2.5 Reinforced Flexural Capacity. The nominal flexural capacity shall be determined following the assumptions given in ACI CODE-318, Section 22.2. Elements shall be proportioned such that they are tension-controlled, defined as the strain in the reinforcement being no less than 0.005. The nominal flexural capacity shall not be less than 1.3 times the nominal cracking moment capacity, M_{cr}. The modulus of rupture shall be calculated as follows: $7.5\sqrt{f_c'}$.

404.4.2.6 Reinforced Shear Capacity. The nominal shear capacity shall be equal to

$$V_n = 8(\rho)^{1/3}\sqrt{f_c'}b_w d \ \leq \ 2\sqrt{f_c'}b_w d$$ (ACI CODE-318 Section 22.5.5.1).

where ρ is equal to the ratio of A_s to the shear area. A_s shall be computed as the area of longitudinal reinforcement located at least 2/3 of the overall element depth away from the extreme compression fiber.

When designing cores, cross ties shall be neglected in determining the shear capacity.

404.4.2.7 Deflection Criteria. Out-of-plane deflection of 3D-ACT wall systems containing or supporting unreinforced elements shall be limited to $l/600$ for simply supported spans and $l/300$ for cantilever spans. For 3D-ACT wall systems not containing or supporting unreinforced elements, deflection shall be in accordance with the building code adopted by the administrative authority adopting this standard as applicable for the intended use of the structure.

404.5 Axial Loads and Combined Moment and Axial Loads. 3D-ACT wall systems shall be designed for axial loads in accordance with this section. Where both out-of-plane loads and axial loads act on the 3D-ACT wall system, the effects of combined moment and axial loads shall be considered.

404.6.5 General. 3D-ACT wall systems shall be designed ignoring the contribution of the longitudinal reinforcement in calculating the axial load-carrying capacity. If longitudinal reinforcement is required, pilasters or columns shall be included in the 3D-ACT wall system.

404.5.2 Minimum Wall Dimensions. The minimum thickness, h_{eff}, in load-bearing walls shall be the greater of 4 in. (100 mm) or the wall height in inches divided by 25. Thinner walls are permitted if adequate strength and stability can be demonstrated by structural analysis.

404.5.3 Axial Load Capacity. If the resultant of all factored loads is located within the $h_{eff}/6$ of the centroid of the wall, the nominal axial capacity shall be equal to:

$$P_n = 0.55f_c'A_g\left[1-\left(\frac{kl_c}{32h_{eff}}\right)^2\right]$$ (ACI CODE-318, Equation 11.5.3.1)

where k shall be in accordance with Table 404.5.3 and l_c is the height of the wall.

Table 404.5.3 Effective Length Factor for Wall

Boundary Condition	***k***
Walls braced both at top and bottom against lateral translation and:	
(a) Restrained against rotation at one or both ends (top, bottom, or both)	0.8
(b) Unrestrained against rotation at both ends	1.0
Walls not braced against lateral translation	2.0

404.5.4 Combined Moment and Axial Loads. 3D-ACT wall systems shall be designed for combined moment and axial loads. Load-bearing walls shall be designed for the maximum strength-level moment, which accompanies the strength-level axial load for each applicable load combination. If the strength-level axial load is less than $0.10f_c'A_g$

and located within $h_{eff}/6$ of cross-section's centroid, axial loads may be neglected and the section can be designed for moment only.

Where the combined effects of moment and axial loads are required to be considered, the nominal capacity of the wall shall be determined following the assumptions given in ACI CODE-318, Section 22.2 to generate an axial-moment interaction diagram. The axial-moment interaction diagram shall not exceed the axial capacity determined according to Section 404.5.3.

404.6 In-Plane Loads. 3D-ACT wall systems shall be designed for in-plane loads in accordance with this section.

404.6.1 Limitations. In-plane ultimate shear loads shall not exceed $\phi\sqrt{f_c'}A_{cv}$.

403.6.2 Flexural Capacity. The nominal capacity of the wall subject to in-plane moments shall be determined following the assumptions given in ACI CODE-318, Section 22.2. 3D-ACT wall systems shall be designed for combined in-plane moment and axial loads. Load-bearing walls shall be designed for the maximum strength-level moment, which accompanies the strength-level axial load for each applicable load combination.

404.6.3 Shear Capacity. The nominal capacity of the wall subject to in-plane shear shall be equal to

$$V_n = 0.6A_{vf}f_y$$

404.6.4 Deflection Criteria. In-plane deflection shall be limited to $l/600$.

404.7 Bearing. 3D-ACT wall systems shall be designed for bearing due to concentrated loads in accordance with this section.

404.7.1 Bearing Capacity. The nominal bearing capacity shall be calculated as $0.85f_c'$ times the bearing area.

404.7.2 Bearing Area. The bearing area, A_{br}, for concentrated loads shall be calculated in accordance with Table 404.7.2.

Table 404.7.2 Bearing Area

Geometry of Bearing Area	Bearing Area, A_{br}
Supporting surface is wider on all sides than the loaded area	Lesser of $A_1\sqrt{A_2/A_1}$ and $2A_1$
Other cases	A_1

Notes:
The area, A_1, is the loaded area but not greater than the bearing plate or bearing cross-sectional area.
The area, A_2, is the area of the lower base of the largest frustum of a right pyramid that has the area, A_1, as its upper base and is wholly contained within the section. The sides of the pyramid shall be sloped 1 vertical to 1 horizontal.

404.8 Concentrated Loads. The distribution of concentrated loads shall be permitted over a length of wall equal to the least of (a) through (c):

(a) The length of bearing area plus the length determined by considering the concentrated load to be dispersed along a line sloped at 2 vertical units to 1 horizontal unit. The dispersion shall terminate at half the wall height, a movement joint, the end of the wall, or an opening, whichever provides the smallest length.

(b) Where a concentrated load is applied adjacent to an opening or the end of the wall, the length of bearing area plus the length determined by considering the concentrated load to be dispersed along a line sloped at 3 vertical units to 1 horizontal unit. The dispersion on each side shall terminate independently at half the wall height, a movement joint, the end of the wall, or an opening, whichever provides the smallest length.
(c) One-half the distance to adjacent concentrated loads.

404.9 Openings. Openings in 3D-ACT wall systems shall be designed in accordance with this section.

404.9.1 Lintels and Headers. Openings wider than 16 in. (400 mm) shall include steel lintels or 3D-ACT headers over opening. Steel lintels shall be designed in accordance with ANSI/AISC 360. 3D-ACT headers shall be designed in accordance with Section 404.5.2. The calculated deflection of lintels and headers providing vertical support to portions of the 3D-ACT wall systems shall not exceed $l/600$ under service dead and live loads.

404.9.2 Minimum **Reinforcement.** 3D-ACT headers shall contain no less than one #4 bar placed within 6 in. (150 mm) of the bottom of the header. Horizontal reinforcement shall be provided at the bottom and top of wall openings and shall extend at least 24 in. (600 mm) but not less than 40 bar diameters past the opening.

Integral cores with vertical reinforcement consisting of one #4 bar or larger shall be provided within 16 in. (400 mm) of each side of openings. Vertical reinforcement adjacent to openings need not be provided for openings smaller than 16 in. (400 mm), unless distributed vertical reinforcement is interrupted by such openings.

404.10 Bond Beams. The design of bond beams shall be designed in accordance with Section 404.5.2. Bond beams shall contain one continuous #4 bar or larger located within 6 in. (150 mm) of structurally connected floors and roofs. The calculated deflection of bond beams providing vertical support to portions of 3D-ACT wall systems shall not exceed $l/600$ under service dead and live load.

404.11 Strength Reduction Factors. The nominal strength of 3D-ACT wall systems determined in accordance with Sections 404.4-404.7 shall be reduced by the strength reduction factors, ϕ and ϕ_{3D}, given in Table 404.11.

Table 404.11 Strength Reduction Factors for 3D-ACT Wall Systems

Limit State	ϕ	ϕ_{3D}
Axial	0.65	0.80
Combined Axial and Flexure	For $\varepsilon_s < \varepsilon_y \rightarrow 0.65$ For $\varepsilon_y \leq \varepsilon_s < \varepsilon_y + 0.003 \rightarrow 0.65 + 0.25\frac{\varepsilon_s - \varepsilon_y}{0.003}$ For $\varepsilon_s \geq \varepsilon_y + 0.003 \rightarrow 0.90$	0.80 0.80 0.95
Unreinforced Concrete	0.60	0.95
Flexure	0.90	0.95
Shear	0.75	0.85
Bearing	0.65	0.95

404.12 Reinforcement Development. The required tension or compression reinforcement shall be developed on each side of the critical section by development length, standard hook, mechanical device, or combination thereof. Hooks and headed bars shall not be used to develop bars in compression. Development length shall be determined in accordance with this section.

404.12.1 Filled Elements. This section shall apply to the development length of bar and wire in filled elements such as cores, headers, and bond beams.

404.12.1.1 Grout and Concrete. This section shall apply to bar and wire embedded in grout or concrete in filled elements.

1. For straight deformed bar and wire in tension, the development length shall be calculated in accordance with ACI CODE-318, Section 25.4.2.
2. For hooked deformed bar and wire in tension, the development length shall be calculated in accordance with ACI CODE-318, Section 25.4.3.
3. For headed deformed bar in tension, the development length shall be calculated in accordance with ACI CODE-318, Section 25.4.4.
4. For deformed bar and wire in compression, the development length shall be calculated in accordance with ACI CODE-318, Section 25.4.9.

404.12.1.2 3D Printing Materials. This section shall apply to bar and wire embedded in *3D printing materials* in filled elements.

404.12.1.1 Straight Deformed Bar and Wire in Tension. The development length of deformed bar and wire shall be determined as follows, but shall not be less than 12 in. (300 mm) Development length of epoxy-coated deformed bar and wire shall be taken as 150 percent of the uncoated bar and wire.

$$l_d = 48d_b$$

404.12.1.2 Hooked Deformed Bar and Wire in Tension. The required development length of bars and deformed wires terminating in a standard hook shall be determined as follows, but not less than 6 in (150 mm).

$$l_{dh} = l_d - 9d_b$$

404.12.2 Printed Beads. This section shall apply to the development length of bar and wire in printed beads. The development length of deformed bar and wire in tension shall be determined as follows, but not be less than 12 in. (300 mm).Development length of epoxy-coated deformed bar and wire shall be taken as 150 percent of the uncoated bar and wire.

$$l_d = 60d_b$$

404.13 Reinforcement Splices. Tension splice length for deformed bars and wires in tension in filled elements shall be at least $1.0l_d$ or 12 in. (300 mm), whichever is greater. Tension splice length for deformed bars and wires in tension in printed beads shall be at least $1.2l_d$ or 12 in. (300 mm), whichever is greater.

SECTION 405 CONNECTIONS

405.1 General. 3D-ACT wall system mechanical connections shall be designed in accordance with this section. The requirements herein shall not prevent the use of an equivalent connection method as approved by the administrative authority adopting this standard.

405.2 Design Requirements. The floor and roof diagrams shall be connected to and provide lateral support to the 3D-ACT wall system. 3D-ACT wall systems shall not be connected to structural frames unless the connections and walls are designed to resist design interconnecting forces and to accommodate calculated deflections.

Core reinforcement shall be connected to the foundation using lap splices, couplers, or equivalent means. Connection design shall consider out-of-plane forces, in-plane forces, and axial forces, including net uplift. Roof and floor diaphragms shall be securely anchored to 3D-ACT wall system using bolts, anchors, or reinforcement.

Connection design values shall be based on properly substantiated manufacturer's data, engineering analyses, or full-scale testing consistent with the intended end use. Connections that do not conform to the requirements of this section shall be approved in accordance with Section 406.

Mechanical connections in 3D-ACT wall systems shall be embedded in filled elements, such as cores and bond beams. The minimum permissible effective embedment length shall be the greater of 4 times the fastener diameter or 2 in. (50 mm) Fasteners placed in the top of cores or bond beams shall be positioned to maintain a minimum of 1/2 in. (12.7

mm) between the fastener and the *3D printing material*. Fasteners installed in drilled holes in the face of the shells shall be permitted to contact the *3D printing material* where the fastener passes through the shell, but the portion of the fastener that is within the filled core or bond beam shall be positioned to maintain a minimum of 1/2 in. (12.7 mm) between the fastener and *3D printing material*. The effective embedment depth shall neglect the shell, unless tested in accordance with Section 406.

405.3 Engineering Provisions. Structural anchors and mechanical connections to the 3D-ACT wall system shall be designed based on physical testing or following the ACI CODE-318, Chapter 17. Connection to the non-3D-ACT wall systems shall be designed in accordance with the building code adopted by the administrative authority adopting this standard as applicable for the intended use of the structure.

SECTION 406 ALTERNATIVE STRUCTURAL DESIGN AND TESTING PROVISIONS

406.1 General. The design and detailing of structural elements of 3D-ACT wall systems, including their connections to other structural elements, shall comply with the engineering design in Sections 403, 404, and, where applicable, 405. However, it shall be permitted to determine the structural design of 3D-ACT wall systems through alternative testing requirements of this section. This may include one or a combination of, the complete structural testing described in Section 406.3, anchor testing described in Section 406.4 or select supplemental testing and engineering design described in Section 406.5. Where deviations to the engineering design are used, testing shall show that the alternative method provides equal or better performance than the minimum requirements outlined in Sections 403, 404, and 405.

406.2 Alternative Design Qualification Approach. Full-scale structural testing, anchor testing, supplemental testing, or a combination of testing of a specific 3D-ACT wall system shall be performed by a qualified testing agency complying with ISO/IEC Standard 17025 by any accreditation body that is a signatory to the International Laboratory Accreditation Cooperation (ILAC) Mutual Recognition Arrangement (MRA). For full-scale structural testing described in Section 406.3, an Engineered Design Guidelines Report shall be developed. For supplemental testing described in Section 406.4 and 406.5, a Summary Test Report shall be developed. In either case, the report(s) shall summarize the design of the specific 3D-ACT wall system and demonstrate that it complies with the intent of this standard and the applicable building code.

406.2.1 Testing Agency. Testing shall be performed under the supervision of a licensed design professional that is **independent** of the contractor, manufacturer, or supplier of the materials, equipment, or system proposed for construction.

406.3 Full-Scale Structural Testing. Structural testing shall be performed on full-scale test specimens of the 3D-ACT wall system in accordance with this section.

406.3.1 Test Requirements. Testing shall be performed on each 3D-ACT wall system intended to be constructed and shall be representative of all reasonable permutations being considered in the design. Consideration shall be given to the following:

1. Size and spacing of reinforcement, if applicable.
2. Variation in geometry of the shells, such as thickness and width of the beads or printed wall configuration.
3. Geometry and spacing variation of the cores, if applicable.
4. Wall-to-roof, wall-to-floor, and wall-to-foundation connections.
5. Minimum and maximum time intervals between extrusion layers, including the following:
   a. Time from one extrusion layer to the next immediate extrusion layer.
   b. Time from last extrusion layer prior to placement of floor or roof, to the following extrusion layer above the floor or roof.
6. *3D printing materials* and *3D printer* combination(s), i.e., the 3D printing system, to be used.

406.3.2 Test Specimens and Procedures. The number and type of test specimens shall be in accordance with this section. Unless otherwise specified, destructive testing shall continue until the ultimate load in each case is achieved.

406.3.2.1 Effective Structural Contact Width. The effective structural contact width shall be determined following Section 404.3.1.

406.3.2.2 Effective Side Face Contact. The effective side face contact shall be determined **following** Section 404.3.2.

406.3.2.3 Axial Compression Tests. A minimum of six specimens, with three replicate specimens of two different wall heights, shall be tested. One set of replicate specimens shall be of the maximum wall height with the minimum wall thickness being evaluated.

Axial compression specimens shall be tested in accordance with the general guidelines of ASTM E72 until ultimate load is reached. Axial load shall be applied with a minimum eccentricity of $h/6$, where h is the total thickness of the wall being tested.

406.3.2.4 Out-of-Plane Flexural Tests. A minimum of six specimens shall be tested. The specimen preparation and dimensions shall be the same as those used in the axial compression tests.

Wall flexural specimens shall be tested in accordance with the general guidelines of ASTM E72. The loading in the out-of-plane direction shall be applied by third-point loading until ultimate load is reached.

406.3.2.5 Static In-Plane Shear Tests. A minimum of three replicate specimens with the minimum total wall thickness shall be tested. If multiple wall thicknesses are being evaluated, an additional three replicate specimens of the maximum total wall thickness to be considered shall be tested.

Shear tests shall be performed based on the racking load procedure described in Section 14 of ASTM E72. For these tests, the loading procedure shall be modified to apply the lateral racking through a continuous, reinforced concrete or steel member. The attachment to the specimen shall be designed so that applied loads are uniformly distributed along the specimen length. The specimen shall be mounted on a base in a manner equivalent to the method commonly used in the field. In this regard, the attachment of the specimen to the base shall be constructed to avoid concentrated reaction. In addition, where the vertical load is not sufficient to resist the overturning moment, anchorage shall be incorporated to prevent premature failure due to this action. The procedures and details of the specific test setup will depend on the product or system being tested, and these procedures and details shall be fully documented in the Engineered Design Guidelines Report. Calculations and reporting shall be in accordance with Section 14.5 of ASTM E72.

Alternatively, for 3D-ACT wall systems consisting of two outer face shells and fully filled to form a solid wall, diagonal tension (shear) tests may be performed in accordance with the diagonal shear test procedure as defined in ASTM E519. The ultimate shear stress, ultimate shear strain, and modulus of rigidity for each specimen shall be reported in accordance with ASTM E519.

406.3.2.6 Wall Connection Load Transfer Tests. A minimum of three replicate specimens of each connection between the intermediate floors and the 3D-ACT wall system shall be tested with the minimum total wall thickness being evaluated. If multiple wall thicknesses are being evaluated, an additional three replicate specimens of the maximum total wall thickness shall be tested.

Tests shall be conducted for out-of-plane bending and vertical shear effects of 3D-ACT wall system and each floor connection, and for horizontal shear transfer between the 3D-ACT wall system and each floor system.

406.3.2.6.1 Out-of-Plane Bending and Vertical Shear Effects. A testing apparatus as shown in Figure 406.3.2.6.1, or equivalent, shall be used for this test. The distance L shall be determined such that it represents typical moment-to-shear ratios at the connection for the floor types and boundary conditions being evaluated. A constant vertical load shall be applied on the wall to simulate service conditions. The floor shall be loaded monotonically in the same direction as in-service conditions until wall or floor failure, or both. Each type of floor system shall be tested separately. All failure modes, ultimate loads, and deflection measurements shall be recorded and reported.

406.3.3.7.2 Horizontal Shear Transfer. A testing apparatus as shown in Figure 406.3.3.7.2, or equivalent, shall be used for this test. The wall height shall be at least 7 × thickness of the floor system. The floor shall be loaded monotonically with uniformly distributed loading in the in-plane transverse direction. Each type of floor system shall be tested separately. All failure modes, ultimate loads, and deflection measurements shall be recorded and reported.

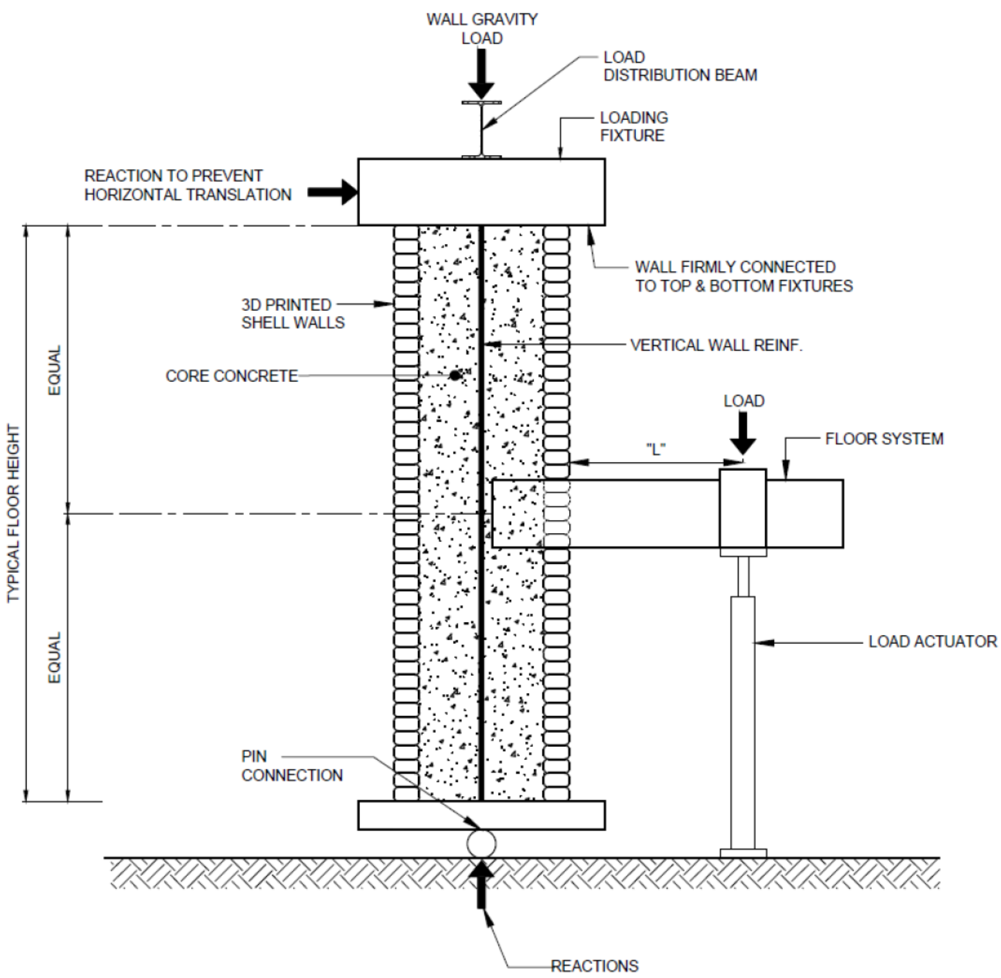
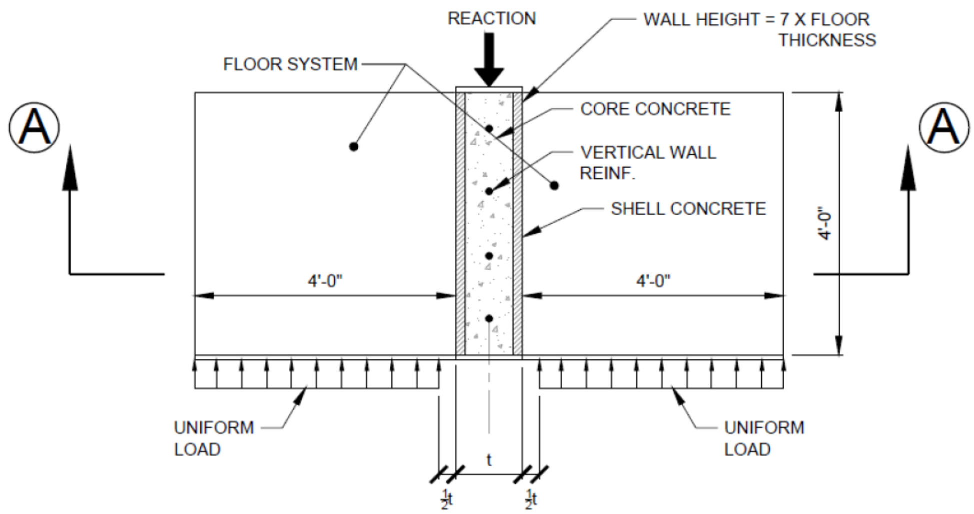
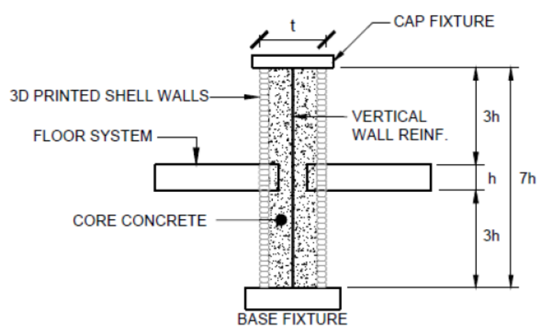


FIGURE 406.3.2.6.1 - WALL CONNECTION LOAD TRANSFER TEST ASSEMBLY FOR OUT-OF-PLANE BENDING AND VERTICAL SHEAR EFFECTS AT WALL/FLOOR JOINT



PLAN VIEW



SECTION A-A

FIGURE 406.3.3.7.2 - WALL CONNECTION LOAD TRANSFER TEST ASSEMBLY FOR HORIZONTAL SHEAR TRANSFER AT WALL/FLOOR JOINT

406.3.2.8 Companion Materials Samples. Companion *3D printing material* samples shall be prepared and cured in the laboratory according to ASTM C192/C192M prior to testing in accordance with Section 303.2. Within 24 hours after the full-scale tests, three replicate samples corresponding to each wall specimen shall be compression tested in accordance with Section 303.2 for correlation of results with the full-scale tests. The as-tested average compressive strength of both the shells and cores shall not be less than the minimum design compressive strength specified in Section 404.2.1.2.

406.3.3 Engineered Design Guidelines Report. An Engineered Design Guidelines Report shall be generated and shall include the following:

1. Summary of the testing performed, including the specimen geometry and details, specimen fabrication, testing equipment and protocol.

2. Results of structural test results performed in accordance with Section 406.3 and as given in the referenced test standards.
3. Analysis of the full-scale structural testing in accordance with Section 406.3.3.1.
4. Load-resistance rating for the 3D-ACT wall system being evaluated in accordance with Section 406.3.3.2.

In addition to the standard reporting and certification of test results, observations, deflections, and loads shall be reported and photographs included capturing the specimens' response at significant stages of the loading process.

406.3.3.1 Analysis of Test Results. When analyzing and interpreting the full-scale structural testing, the average maximum strength from each set of replicate tests may be the average ultimate value, provided the ultimate value for each test is within 15 percent of the average. Otherwise, the lowest ultimate value of the replicate tests shall be used.

406.3.3.2 Load-Resistance Rating. The Engineered Design Guidelines Report shall calibrate, substantiate, and demonstrate a load-resistance rating for the specific 3D-ACT wall system that complies with the intent of this standard. Where applicable, the effect of buckling and/or face spalling of the 3D-ACT wall system shall also be considered in establishing the load-resistance rating.

406.3.3.2.1 Design Methodologies. Relating the load-resistance rating to design code equations, models, and techniques from ACI CODE-318, TMS 402/602, or other applicable codes shall be permitted. Such existing code equations and models shall be modified by appropriate strength reduction factors to verify or modify the existing design equations used to determine characteristic strengths of the 3D-ACT wall system. The design strength of the 3D-ACT wall system reflected in the Engineered Design Guidelines Report shall not be higher than that determined using the strength reduction factors in ACI CODE-318.

406.4.1 Approval. The Engineered Design Guidelines Report shall be available to the administrative authority adopting this standard.

406.4 Anchor Testing. The capacity of anchors in *3D printing materials* may be determined in general accordance with ICC ES AC01, AC58, AC60, AC70, AC106, AC193, AC308, AC398, AC510 and AC545, as applicable. A Summary Test Report shall be generated that includes a summary of the anchor testing performed, including the specimen geometry and details, specimen fabrication, testing equipment and protocol. Deviations or adjustments to the standard test method(s) shall be noted. The Summary Test Report shall be available to the administrative authority adopting this standard.

406.5 Additional Supplemental Testing. Other supplemental testing shall be permitted to accompany the testing described in Section 406.3 or to validate alternatives to the engineering design described in Sections 403, 404, and 405. In either case, this supplemental testing may consist of material testing, small-scale structural testing, or full-scale structural testing to assess a specific engineering property or behavior. Where possible, testing shall follow appropriate ASTM test methods, with the results and any modifications included in the test report. A Summary Test Report shall be generated and shall include a summary of the testing performed, including the specimen geometry and details, specimen fabrication, testing equipment and protocol. Deviations or adjustments to the standard test method(s) shall be noted. Where the testing serves to validate an alternative to the requirements of Sections 403, 404, or 405, the test report shall confirm that the alternative provides equal or better performance than the minimum requirements outlined in Sections 403, 404, and 405. The Summary Test Report shall be available to the administrative authority adopting this standard.

CHAPTER 5

3D PRINTING MATERIAL AND STRUCTURAL FIELD PREQUALIFICATION – TESTING METHODS, PERFORMANCE REQUIREMENTS AND FINAL ACCEPTANCE

SECTION 501 FIELD PREQUALIFICATION TESTING

501.1 General. The provisions of this section govern the field prequalification of the *3D printing material* and *3D printing material mix design* in combination with the 3D printing system. The *3D printing material* and *3D printing material mix design* shall meet the requirements of Chapter 3 of this standard prior to performing the field prequalification testing.

Prequalification testing shall be performed on specimens printed using the *3D printing materials*, with the *3D printing material mix design*, and 3D printing system proposed for construction. Each *3D printing material mix design* and 3D printing system model combination including the mixing, delivery, and extrusion equipment intended to be used in the construction project requires prequalification testing in accordance with this section to evaluate compatibility and execution.

Variation in environmental conditions shall be taken into consideration while the prequalification tests are carried. Additional prequalification testing shall be performed if the ambient conditions of a project vary by more than ±20°F (±11°C) temperature or by more than ±20% humidity from the average daily temperature and relative humidity recorded during the prequalification testing.

501.2 Material Source and Storage Requirements. Materials sourced for the field prequalification shall be consistent with those used in the laboratory prequalification in Chapter 3 of this standard and shall be listed in the *3D printing material mix design*. Materials shall be stored in a manner that prevents deterioration or any condition that would alter material properties such as the introduction of unaccounted for moisture prior to mixing and batching. Where individual constituent materials for field mix are sourced and stored separately, their storage shall be in accordance with ready-mix concrete standard practice per ASTM C94/C94M and ASTM C685/C685M.

501.3 Prequalification Elements. For prequalification there shall be a minimum of two unreinforced prequalification elements that are used for the extraction of specimens for testing the representative hardened material properties. The geometry of the prequalification elements shall conform to the dimensions and details shown in Figure 501.3. Each test print specimen shall consist of 16 layers above the initial layer (17 layers total). The bead dimensions shall be such that the cut dimensions of the samples comply with the requirements of the subsequent tests specified in this section. If *3D printing concrete* is used for construction, the bead size shall be such that it will allow extraction of sawn samples for compression tests mentioned in Section 501.6.2.1 with a minimum dimension of four times the maximum aggregate size.

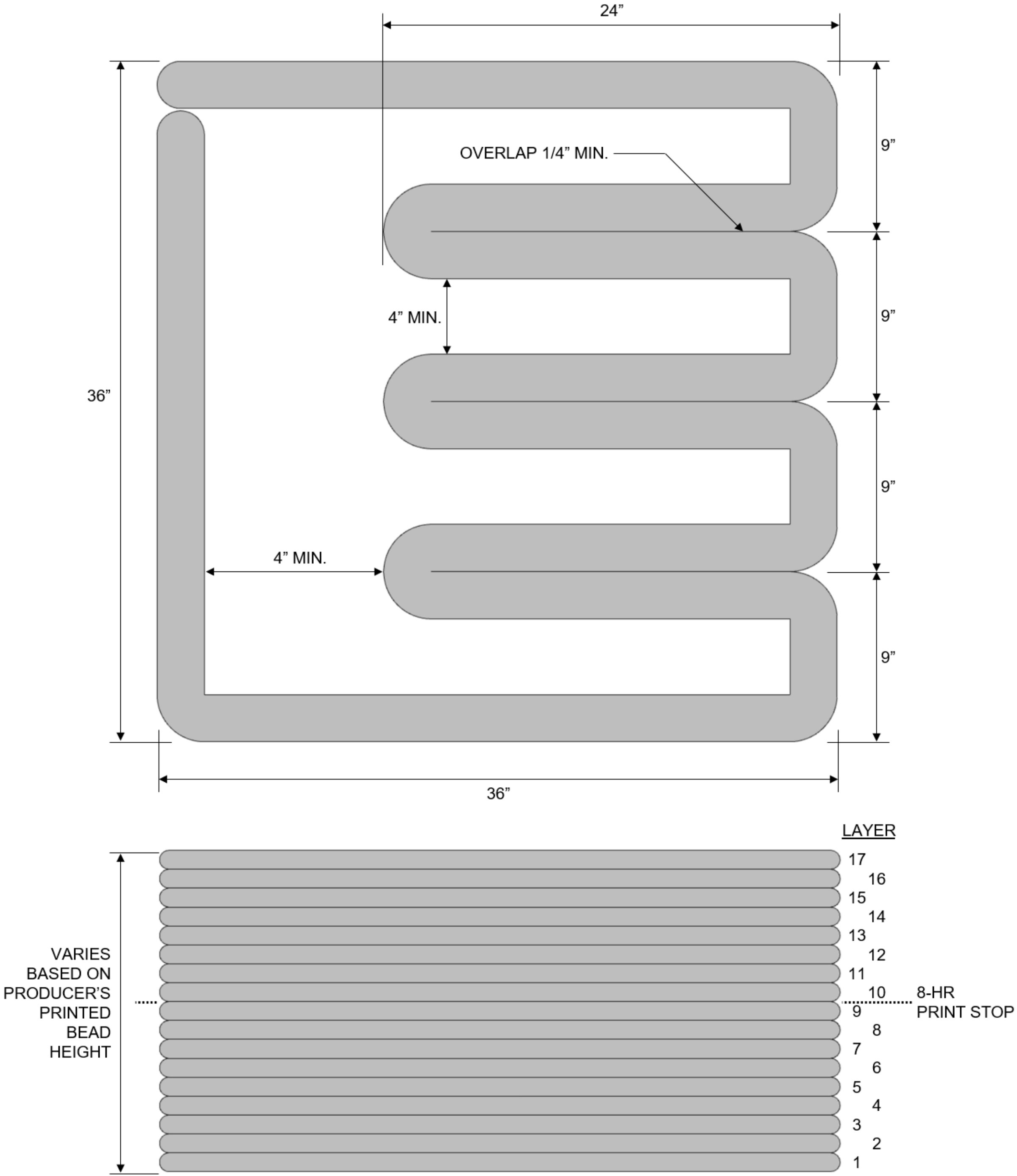


FIGURE 501.3 PREQUALIFICATION ELEMENT GEOMETRY
(TOP: PLAN VIEW; BOTTOM: ELEVATION VIEW)

501.4 Printing Process. *3D printing material* batching, mixing, and printing shall follow the standard operating procedures of the material supplier and producer with the following requirements. The time between layer extrusions shall be the typical interlayer print time except for:

1. The delay between print layers 8 and 9, and 10 and 11 shall be the maximum interlayer print time that will be used during construction without application of bonding agent or special surface preparation between

printing layers. During construction, there shall be no application of bonding agent or special surface preparation between printing layers.

2. A print stop of at least 8 hours shall be incorporated between layers 9 and 10. The producer's print stop interlayer protocol shall be followed prior to resuming printing. The print stop protocol may consist of the application of a bonding agent or other surface preparation techniques when used in the construction. The protocol shall be documented as part of the submittal and incorporated into the construction documents.

3D printing material produced at the plant of a ready-mixed concrete supplier shall conform to the requirements of ASTM C94/C94M. *3D printing material* produced using volumetric batching shall conform to the requirements of ASTM C685/C685M. Material batching, mixing, delivery, and printing for the prequalification elements shall be consistent with temperature and relative humidity conditions anticipated during construction.

The early-age protection and curing shall replicate the means and methods intended to be used for the specific construction project. Where specific early-age protection and curing procedures are implemented, they shall be documented as part of the submittal and incorporated into the construction documents.

501.5 Print Logs. Logs documenting the material batching, printing system details, batching information, admixture dosages, layer print times, and print ambient environmental conditions shall be maintained and made available upon request by the licensed design professional or the administrative authority adopting this standard.

501.6 Testing. Tests shall be performed to verify the properties of the *3D printing material* after extrusion.

501.6.1 Fresh Properties. The fresh properties of *3D printing material* shall be measured in accordance with this section using the test methods specified therein unless explicitly indicated otherwise. *3D printing material* shall be sampled and tested at the start of printing, when printing is resumed after the 8 hour print stop, and when printing is complete. All the samples shall be collected from the nozzle and tests shall be repeated on samples collected at all three points in time.

501.6.1.1 Workability. The workability of the freshly mixed *3D printing material* shall be determined in accordance with ASTM C1437 for *3D printing mortar* and in accordance with ASTM C143/C143M for *3D printing concrete*. Where ASTM C1437 is used, a steel mounting plate with a minimum thickness of 3/4 in. (19 mm) and a minimum weight of 35 lb. (16 kg) may be used in lieu of the concrete pedestal for field applications.

501.6.1.2 Air content. The air content of the *3D printing material* shall be determined in accordance with ASTM C231/C231M.

501.6.1.3 Density (unit weight). The density of *3D printing concrete* shall be determined in accordance with ASTM C138/C138M. The density of *3D printing mortar* shall be determined in accordance with ASTM C185.

501.6.1.4 Strength Test Specimens. A minimum of six specimens for compression strength tests shall be molded from each prequalification element. The specimens for *3D printing mortar* shall be 2 in. (50 mm) cube specimens molded in accordance with ASTM C109/C109M or cylinder specimens molded according to ASTM C39/C39M. The specimens for *3D printing concrete* shall be cylinder specimens molded in accordance with ASTM C39/C39M.

501.6.2 Hardened Properties. The hardened properties of *3D printing concrete* and mortar shall be measured in accordance with this section using the test methods specified therein unless explicitly indicated otherwise.

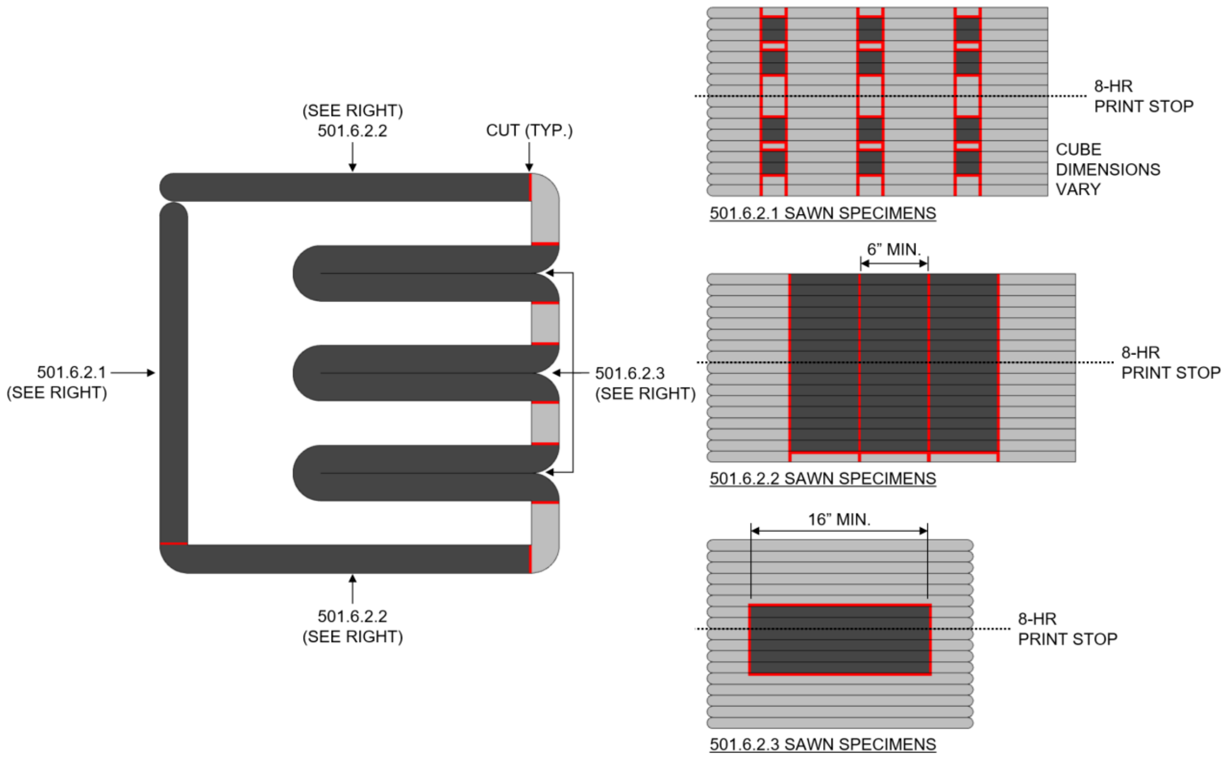


FIGURE 501.6.2.1 SAWN SPECIMEN GEOMETRY

501.6.2.1 Compressive Strength. Specimens shall be cured according to ASTM C31/C31M. *3D printing mortar* specimens shall be tested in accordance with ASTM C109/C109M for cubes and ASTM C39/C39M for cylinders. 3D printed concrete cylinders shall be tested according to ASTM C39/C39M.

In addition, a minimum of 24 specimens, 12 per prequalification element, shall be sawn from the single-bead portions of the test specimens. Saw cutting of specimens is shown Figure 501.6.2.1. Dimensional tolerances of the samples shall meet the requirements for sawn beam specimens in ASTM C42/C42M. Testing shall be performed in accordance with ASTM C109/C109M with five samples tested parallel to the interface and print direction and five samples tested perpendicular to the interface and print direction for each prequalification element. Each cube shall include at least one interface. For *3D printing mortar* where nominal width according to ASTM C109/C109M is not achievable, the minimum width of the cubes will be a minimum 90 percent of the effective structural contact width between layers, and the load rate shall be modified to impart a stress rate equivalent to what is specified in ASTM C109/C109M. Similarly, for *3D printing concrete* samples, procedures in ASTM C109/C109M shall be followed for testing, and the load rate shall be modified to impart a stress rate equivalent to what is specified in ASTM C109/C109M. The specimen weight, dimensions, compressive strength, and failure modes shall be reported. The design compressive strength of the material shall be established using these test results with consideration of the statistical variability in the material properties.

501.6.2.2 Interlayer Flexural Bond Strength. A minimum of 12 specimens with minimum dimension of 6 in. (150 mm) wide by 16 courses, six per prequalification element, shall be sawn from the single bead portions of the prequalification element. Samples shall be extracted such that the 8 hour print stop is contained within the middle third of the sample. Testing shall be performed in accordance with Method A in ASTM E518. The sample weight, dimensions, and modulus of rupture shall be reported.

501.6.2.3 Interlayer Tensile Bond Strength. A minimum of 24 specimens, 12 per prequalification element, shall be tested following ASTM C1583 as modified herein.

Test specimens shall be sawn from the double-bead portions of the prequalification elements and shall contain at least six layers, with the 8 hour print stop at the top 1/3 height of the specimens. Specimens shall be at least 16 in. (400 mm)] long to ensure stability during coring operations. While core drilling vertically for ASTM C1583 pull-off testing, the testing specimens shall be secured in a manner to minimize or prevent wobbling and vibration during coring. Coring shall penetrate at least three interfaces, including the 8 hour stop layer.

Pull-off testing shall use test discs with a diameter no larger than 90 percent of the single-bead effective structural contact width. The core barrel's inner diameter shall match the diameter of the test disc. The distance from the center of a tensile bond test to a free edge is permitted to be less than 2 in. (50 mm) Tests are permitted to be reported as individual results rather than sets of three similar failure modes. The failure load, test diameter, and failure type shall be reported. Tests including the overnight print stop shall be clearly designated.

501.6.2.4 Additional Testing. Additional tests and test methods may be performed at the discretion of the material supplier, producer, or both but are not required for field prequalification.

501.7 Submittal Requirements. Upon completion of the field prequalification, a submittal shall be provided to the licensed design professional that demonstrates suitable properties for workability, structural performance, and durability for the intended construction project. The submittal shall include the following:

a) Information about the constituent materials or the technical datasheet of the pre-packaged products and evidence of compliance with this standard,
b) Mixture proportions and characteristics including the proposed ranges of mixture proportions and changes in *3D printing materials* to adjust mixtures to accommodate changes in project and to comply with contract documents,
c) Batching instructions, batching sequence, mixing times, and waiting times,
d) Acceptable flow or slump and air content ranges measured at the point of extrusion,
e) Fresh, hardened, and durability properties determined from laboratory prequalification testing,
f) Fresh and hardened properties determined from field prequalification testing,
g) Fresh and hardened properties determined from full-scale structural testing performed in accordance with Section 405, where applicable,
h) Print stop interlayer protocols, where applicable, and
i) Early-age protection and curing procedures, where applicable.

501.8 Re-qualification. Field prequalification shall be repeated yearly or whenever a substantive change is made to the *3D printing materials*, mixture design, or 3D printing system, whichever is more frequent.

SECTION 502 FIELD FINAL ACCEPTANCE TESTING

502.1 General. All the sampling material for field final acceptance testing shall be collected from the extruding nozzle or the printing head except for compression tests performed on cut specimens from printed walls. All the following testing or specimen casting shall be finished within five minutes of material sampling except for cut samples. The ambient temperature and relativity humidity of the field conditions shall be reported.

502.2 Workability. The workability of the *3D printing material* shall be determined in accordance with ASTM C1437 for flow of *3D printing mortar* or in accordance with ASTM C143/C143M for slump of *3D printing concrete*. Where ASTM C1437 is used a steel mounting plate with a minimum thickness of ¾ in. [19 mm] and a minimum weight of 35 lbf (16 kg) may be used in lieu of the concrete pedestal for field applications. At a minimum, one test shall be performed at the nozzle before printing operations start to verify that the material meets the workability requirements as determined in Section 501.6.1.1 and specified in Section 501.7 of this standard, and additional tests shall be performed halfway through daily printing.

502.3 Air content. The air content of the fresh *3D printing material* shall be performed according to ASTM C231/C231M at the nozzle before printing operations start to verify that the material meets the specified air content as determined in Section 501.6.1.2 and specified in Section 501.7 of this standard, and additional air content tests shall be performed halfway of daily printing.

502.4 Compressive Strength. On cast samples, the compressive tests shall be carried out in accordance with ASTM C109/C109M for 2 in (50 mm) cube specimens or ASTM C39/C39M for cylinder specimens for *3D printing mortar*, and ASTM C39/C39M for cylinder specimens for *3D printing concrete*. Once the desired fresh properties are achieved, compressive strength specimens shall be cast using the extruded materials from the nozzle. Sampling and casting shall be done at least once a day followed by demolding at 24-hours and subsequently wet curing in laboratory conditions until testing ages (7-days and 28-days).

In addition, a minimum of five specimens shall be sawn once a week from either the walls of actual printed structures or a mock-up wall with similar characteristics. Samples may be extracted from any suitable location. Testing shall be performed in accordance with ASTM C109/C109M with the samples tested perpendicular to the interface and print direction. Each cube shall include at least one interface. The specimen weight, dimensions, compressive strength, and failure modes shall be reported.

Compressive strength determined in this section shall comply with the following,

(a) Every average of any consecutive three compressive strength tests shall equal or exceed the specified design strength used in Chapter 4 of this standard.
(b) No strength test shall fall below 90 percent of the specified design strength used in Chapter 4 of this standard.

CHAPTER 6

REFERENCED STANDARDS

ACI

ACI World Headquarters
38800 Country Club Drive
Farmington Hills, MI
48331-3439 USA

318-19: Building Code Requirements for Structural Concrete
PRC-347-14(21): Guide to Formwork for Concrete (Reapproved 2021)

AISC

American Institute of Steel
130 East Randolph Street, Suite 2000
Chicago, IL 60601-6219

ANSI/AISC 360-22: Specification for Structural Steel Buildings

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ASME

American Society of Mechanical Engineers
Two Park Avenue
New York, NY 10016

B89.1.14-2018: Calipers

ASTM

ASTM International
100 Barr Harbor Drive, P.O. Box C700
West Conshohocken, PA 19428-2959

A615/A615M-24: Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement
A641/A641M-19: Standard Specification for Zinc–Coated (Galvanized) Carbon Steel Wire
A706/A706M-24: Standard Specification for Deformed and Plain Low-Alloy Steel Bars for Concrete Reinforcement
A767/A767M-19: Standard Specification for Zinc-Coated (Galvanized) Steel Bars for Concrete Reinforcement
A775/A775M-22: Standard Specification for Epoxy-Coated Steel Reinforcing Bars
A820/A820M-22: Standard Specification for Steel Fibers for Fiber-Reinforced Concrete
A884/A884M-19e1: Standard Specification for Epoxy-Coated Steel Wire and Welded Wire Reinforcement
A934/A934M-22: Standard Specification for Epoxy-Coated Prefabricated Steel Reinforcing Bars
A951/A951M-22: Standard Specification for Steel Wire for Masonry Joint Reinforcement
A955/A955M-20c: Standard Specification for Deformed and Plain Stainless Steel Bars for Concrete Reinforcement
A996/A996M-24: Standard Specification for Rail-Steel and Axle-Steel Deformed Bars for Concrete Reinforcement
A1022/A1022M-22a: Standard Specification for Deformed and Plain Stainless Steel Wire and Welded Wire for Concrete Reinforcement
A1055/A1055M-22: Standard Specification for Zinc and Epoxy Dual-Coated Steel Reinforcing Bars
A1064/A1064M-24: Standard Specification for Carbon-Steel Wire and Welded Wire Reinforcement, Plain and Deformed, for Concrete
C31/C31M-24b: Practice for Making and Curing Concrete Test Specimens in the Field
C33/C33M-24: Standard Specification for Concrete Aggregates
C39/C39M-24: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens

C42/C42M-20: Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
C94/C94M-24c: Standard Specification for Ready-Mixed Concrete
C109/C109M-23: Standard Test Method for Compressive Strength of Hydraulic Cement Mortars
C138/C138M-24a: Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete
C143/C143M-20: Standard Test Method for Slump of Hydraulic-Cement Concrete
C144-18: Standard Specification for Aggregate for Masonry Mortar
C150/C150M-24: Standard Specification for Portland Cement
C157/C157M-24: Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete
C185-20: Standard Test Method for Air Content of Hydraulic Cement Mortar
C192/C192M-19: Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory
C231/C231M-24: Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method
C260/C260M-10a(2016): Standard Specification for Air-Entraining Admixtures for Concrete
C305-20: Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency
C403/C403M-23: Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance
C469/C469M – 22: Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression
C476-23: Standard Specification for Grout for Masonry
C494/494M-24: Standard Specification for Chemical Admixtures for Concrete
C511-21: Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes
C595/C595M-24: Standard Specification for Blended Hydraulic Cements
C618-23e1: Standard Specification for Coal Ash and Raw or Calcined Natural Pozzolan for Use in Concrete
C685/C685M-24: Standard Specification for Concrete Made by Volumetric Batching and Continuous Mixing
C666/C666M-15: Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing
C807-21: Standard Test Method for Time of Setting of Hydraulic Cement Mortar by Modified Vicat Needle
C989/C989M-24: Standard Specification for Slag Cement for Use in Concrete and Mortars
C1077-24: Standard Practice for Agencies Testing Concrete and Concrete Aggregates for Use in Construction and Criteria for Testing Agency Evaluation
C1157/C1157M-23: Standard Performance Specification for Hydraulic Cement
C1240-20: Standard Specification for Silica Fume Used in Cementitious Mixtures
C1260-23: Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)
C1437-20: Standard Test Method for Flow of Hydraulic Cement Mortar
C1583/C1583M-20: Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method)
C1602/C1602M-22: Standard Specification for Mixing Water Used in the Production of Hydraulic Cement Concrete
C1666/C1666M-08(2023): Standard Specification for Alkali Resistant (AR) Glass Fiber for GFRC and Fiber-Reinforced Concrete and Cement
D98-15(2021): Standard Specification for Calcium Chloride
D7357-07(2019): Standard Specification for Cellulose Fibers for Fiber-Reinforced Concrete
D7508/D7508M-20: Standard Specification for Polyolefin Chopped Strands for Use in Concrete
E72-22: Standard Test Methods of Conducting Strength Tests of Panels for Building Construction
E84-24: Standard Test Methods for Surface Burning Characteristics of Building Materials
E329-23: Standard Specification for Agencies Engaged in Construction Inspection, Testing, or Special Inspection
E518/E518M-22: Standard Test Method for Flexural Bond Strength of Masonry

E519/E519M-22: Standard Test Method for Diagonal Tension (Shear) in Masonry Assemblages

ICC

International Code Council, Inc.
500 New Jersey Ave NW
6th Floor
Washington, DC 20001

IBC: International Building Code®
IRC: International Residential Code®
ICC-ES Acceptance Criteria for Expansion Anchors in Masonry Elements - Approved March 2018 (AC01)
ICC-ES Acceptance Criteria for Mechanical Anchors in Cracked and Uncracked Masonry Elements - Approved June 2024 (AC01)
ICC-ES Acceptance Criteria for Adhesive Anchors in Cracked and Uncracked Masonry Elements (AC58)
ICC-ES Acceptance Criteria for Anchors in Unreinforced Masonry Elements (AC60)
ICC-ES Acceptance Criteria for Power-actuated Fasteners Driven into Concrete, Steel and Masonry Elements (AC70)
ICC-ES Acceptance Criteria for Predrilled Fasteners (Screw Anchors) in Masonry (AC106)
ICC-ES Acceptance Criteria for Mechanical Anchors in Concrete Elements (AC193)
ICC-ES Acceptance Criteria for Post-installed Adhesive Anchors and Reinforcing Bars in Concrete Elements (AC308)
ICC-ES Acceptance Criteria for Steel Connectors for Connecting Light-frame Construction Members to Concrete (AC398)
ICC-ES Acceptance Criteria for Seismic Qualification of Post-Installed Anchors in Concrete (AC510)
ICC-ES Acceptance Criteria for 5/16-in (8mm) Diameter and Smaller Unreinforced Masonry Screws (AC545)

ISO

International Organization for Standardization
Chemin de Blandonnet 8 CP 401 1214 Vernier
Geneva, Switzerland

ISO/IEC 17025-17: Testing and calibration laboratories

TMS

The Masonry Society
105 South Sunset Street, Suite Q
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402-22: Building Code Requirements for Masonry Structures
602-22: Specification for Masonry Structures

UL

UL LLC
333 Pfingsten Road
Northbrook, IL 60062-2096

UL 723-18: Test for Surface Burning Characteristics of Building Materials