Free-Form: The Adversarial Role of Materials in Automation

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Abstract

Beyond allowing students to create physical models of complex geometry they would be unable to produce by hand, how can 3D-printing become relevant to studio and in practice? This paper will discuss the underlying dilemma confronting materials in studio education, particularly in the United States. Materials are, in many ways, foreign to the studio process, and this is compounded by the addition of a “foreign” technology, such as computer-aided manufacturing. Materials are more often seen as an aesthetic selection, and their adversarial role (the way in which materials can be unpredictable, counterproductive, and even belligerent) in construction is not essential or deep learning in the studio environment. Design-build education models often seek to confront this dilemma, particularly if they are more focused on research into materials and their fabrication, but even fewer programs utilize technology such as 3D-printing, again because it can be seen as difficult enough to teach students simple manufacturing processes. This paper will discuss five schools pioneering the potential of these tools: the ETH Zurich, the University of Stuttgart, MIT, the Bartlett, and Sci-Arc. While these schools have generated provocative research and compelling full-scale installations, there is also a distinct gap between this research and its dissemination/assimilation into mainstream practice. This paper seeks to understand the gap between possibility and pragmatics by studying these innovative schools’ methodologies and the ways in which their outcomes manifest in studio/practice. In summary, 3D-printing can offer the same potential as any other tool utilized in a design-build studio. It forces students to grapple with a material understanding they can choose to ignore on paper and in a virtual environment. By more literally understanding the conversion of a three-dimensional virtual solid into a sequence of coordinates (the g-code), the mystique of the technology is made equal to that of the wood stud.

Keywords: Materials, Construction, Pedagogy, 3D-printing, Fabrication research, Design-build

Introduction

3D-printing has a ubiquitous cachet in architecture schools. It is mysterious and exciting: by pressing buttons, making your computer talk to a device, and waiting hours, an object appears that is the simulacrum of the digital thing fashioned on the computer. The dream of this technology is to equalize the sophisticatedly complex object with the simplicity of a wood stud. This is an oversimplification, but like CAD drafting, the technology spurred an outpouring of free form making in the studio setting because, as critic Mario Carpo noted, “digital file-to-factory technologies…offer no economies of scale….”[1] As an idealized technological process, it promises to remove the cost inherent in complexity. Even former US President Barack Obama remarked that 3D-printing “…has the potential to revolutionize the way we make almost everything,”[2] creating jobs and transforming the traditional factory.

3D-printing in schools more often than not reinforces the separation between the student/architect and the materials one uses to build, because it is usually seen as an alternative to physical model-making. The plastic filament primarily used to print with is typically understood through settings initially established by the manufacturers, reinforcing this disengagement. When that digital process of creating an object in a virtual world is scaled up into an additive manufacturing process – 3D-printed concrete, for instance – materials take on an adversarial role that cannot be accounted for in the virtual world. Issues such as support structure (literally a scaffold), overhangs, even the pressure the nozzle exerts on the printed form to create adhesion, fight back on that virtual object, preventing it from becoming its actual simulacra. At their core, materials' inherent qualities outplay the tools that manipulate them. This does not mean that concrete, for instance, should be vanquished to allow the architect to 3D-print their dreams. Instead, it forces the architect to understand the nature of the material because, despite its virtual appearance, 3D-printing creates a process-driven form. As Claypool et al postulate, "If we then rethink the industrial robot arm as part of a holistic and procedural design and fabrication process for crafting an object…we transform the way we think about the crafting of material…."[3] The procedure of the robot is as essential to understanding how we can transform the material, as that of the material itself.

Mario Carpo expands on process-driven form*,* "Artisans of pre-industrial times…were not engineers: hence they …. learned intuitively, by trial and error, by making and breaking as many samples as possible. So we do today, using iterative digital simulations."[4] He distinguishes between what he calls "search-based" alternatives to modern science, where digital tools allow designers to process, or search, through many digital trial-runs in order to find a form that holds up structurally and aesthetically. He juxtaposes this methodology to a more deductive, or "causal", engineer-based approach to form-finding. His argument is that causal form-finding employs "small-data logic", creating predictable structures, but that, "Computers can search faster than humans can sort."[5] To search is to locate a (loose) precedent and test it to failure and repeat. To sort is find the science/math/engineering equation that ultimately over-structures design for the sake of the "known." This is the opposite of a technological frontier and actually denies invention.

With digital fabrication, it's more efficient to try something intuitive and then modify and repeat. A material's adversarial role is subdued through design adaptation, often through digital and actual simulation. In the design-build studio setting, materials relatedly require students to encounter the heaviness of a material in the shop/site setting. Lifting and maneuvering materials or assemblies brings to the fore their adversarial role in resisting such operations, forcing the builder/designer to adapt, invent, and try again. An intuitive operation leads to immediate learning. Similar to the pre-industrial artisan, the student, through trial and error, becomes aware of how one physically builds, accounting for the volume of space necessary to erect and fasten materials in situ on a building site. This awareness can extend to the (likely harsh) climatic conditions during construction, or from offsite preassembly and transport logistics.

Design-build, as a methodology, is ripe for the application of Carpo's "search-based" alternatives to traditional form-finding, particularly as a threshold between the artisan and the computer. This studio model is, at its foundations, about exposing students to risk, failure, iteration, and (hopefully) success. A kind of visceral learning occurs in design-build when materials' adversarial nature is confronted, where they fight back against the design intentions. Warping, tearing, cracking, spawling – these are just a few of the active ways in which materials, by their nature, resist the roles in which they are placed in a project. Incorporating the computer, and even bypassing in-person trial and error for digital simulation, still creates that moment of reckoning that is not only critical to students' engagement with built reality, but also to making technology like 3D-printing applicable to the building construction industry.

The Design-Build Studio

The reality inherent to the materials in an architectural project is not an intrinsically learned part of architectural education. Students are exposed to the concepts of dimensional tolerance, taught to draw wall sections, and may even watch videos of construction and/or tour a construction site. But this is akin to reading a book about fishing and assuming one can catch a fish on a first attempt. There is a great deal of complexity in understanding the way a material will behave in the real world, making it challenging to teach without direct experience with those materials.

Historically, construction knowledge has not been deemed necessary to the designing of architecture. Architectural education in the United States developed from the pedagogical models coming out of Germany (the "polytechnic"), France (the Beaux-Arts), and England (the apprenticeship).[6] In general terms, architects in the United States were first trained by working under architects (the English model). When architecture schools were formalized in the traditional university setting, pragmatic training was not lost, but the curriculums adopted either the "polytechnic" model, which was primarily rooted in the "pure" research of construction/structure,[7] or the Beaux-Arts model, which was based on aesthetics and drawing. Marco Frascari's discussion of the Beaux-Arts analytique epitomizes this: "The drawings carried few if any details and dimensions. The designer could be almost entirely dependent on his craftsmen."[8] Many American schools placed more emphasis on the Beaux-Arts/humanist model (particularly with their integration into arts and sciences,[9] which has trickled down to most schools today.

As architect and founding member of the AIA Leopold Eidlitz suggests, "…as human life is too short to enable one man to master practically so many arts, the question to be answered is reduced to this: Shall the pupil of architecture be educated in some mechanical workshop, in an art studio, or in a polytechnical school."[10] Eidlitz understood the dilemma in educating an architect between various discourses from the theoretical/philosophical/critical, the aesthetic, and the mechanical/constructional. Eidlitz was a proponent of the more German model of the "polytechnic", so for him, "How shall I build this thing? Should be the constant question of the architect while composing, instead of what form shall I give it?"[11] But this questioning can be quickly lost in the tides of current trends in architecture, from digital representation to sustainability.

Even the typical AIA contract reinforces the separation between the architect and construction, making the architect responsible solely for the drawings (lines) and specification (words).[12] Construction is understood as the contractor's locale – design occurs in the drawing, downplaying the significance of the building materials and the way in which they are put together. Obviously, this is not to say that every architect must care little for materials and construction, but that the way in which we are taught and the way in which we establish our relationship to the parties that together achieve architecture undermines the relevance that building construction plays in making architecture.

Design-build studios have historically been a way in which to resist this kind of thinking in school, from Frank Lloyd Wright's Taliesen West to Auburn's Rural Studio. Design-build educational models have grown popular in the past 20 years amongst both faculty and students.[13] Most architects agree that an enhanced familiarity with building materials engenders a better understanding of detailing, and, if nothing else, less risk of failures in the built outcome. But an interest in building materials and the way in which they go together can also spark experimentation, where the making of architecture is fundamentally part of the design of its spaces. This harkens back to the "polytechnic," or German model, Eidlitz supports, where the how-it's-made is bound up in the design process itself.

Design-Build programs today fall typically between a much more abstract research-based investigation into a specific material and a more pragmatic professional practice-based project intended to be completed by the students.[14] Both approaches have merits (often beautiful artifacts that are newsworthy) and challenges (application to real building construction and the pedagogical/ethical challenges of forcing practice into the space of a studio). A more middle-ground approach to integrating design-build is *fabrication research*. The exploration is tactile and iterative, making it productive for the students' learning, and it directly supports detailing as a critical practice. Service-learning oriented design-build and more pure materials research also incorporate fabrication, but the emphasis on construction and learning through how things go together is inevitably subservient to the other goals of these studios. Fabrication research directly addresses the adversarial nature of materials, the way they fight back, outmaneuver and change. This method of research also supports failure/refinement by allowing students to play with what is possible, creating a bridge towards material understanding that is fundamental to design.

Fabrication Research

Returning to Carpo's concept of "search-based" form-finding, fabrication research sits at an important, even charged, space between materials research and the pragmatics of constructing a building, because the work is about trial and error, failure and refinement. At its most ideal, fabrication research is where materials, and the methods whereby they are transformed, can be explored, pushed, or fantasized (Fig. 1). By incorporating digital technology (both simulation and manufacturing), the tools and materials can be rethought as hybrids or composites, all as materials push back unexpectedly. Materials are beaten, cut, bored and sculpted, etc., as the search continues for a method of construction that works, potentially modifying the construction technology and rethinking the capabilities of a material. This research offers a window into the adversarial role building materials create, where failure is as important as success. It will shape the way a student will choose to incorporate that material into their projects.

Figure 1. An example of fabrication research, from early experimentation (left), to final prototypes (right).

This teaching methodology is distinct from the typical design-build model, because most design-build hinges on a successfully delivered object/building/product. Design-build objects are often the most newsworthy features of many architectural programs. But fabrication research, including all the work leading up to the final object, is filled with ugly ducklings, mudskippers, and real failures. Understanding failure as a part of the design process, particularly the failure in translation from virtual to real space, is fundamental to any creative activity. Artist Richard Serra speaks to how this process in his own work is made evident:

> "In all my work the construction process is revealed. Material, formal and contextual decisions are self-

> evident. The fact that the technological process is revealed depersonalizes and demythologizes the idealization of the sculptor's craft…. Their construction leads you into their structure and does not enter into or refer the artist's persona."[15]

Serra is not unique in his understanding – he appreciates the role of the construction process as part of the making of the art, because he is not the one physically erecting the work, much like the architect.

The Rise of 3D-printing

3D-printing, or additive manufacturing, remains a foreign technology that has both students and faculty smitten with its potential to create complex "unbuildable" shapes. More often than not, the technology is treated in the same manner as the laser cutter – as a means to speed model production and allow complex shapes to be outputted as they are represented in the computer. The potential for this technology as applied to building construction has been largely overlooked in this context.

But 3D-printing offers a unique way to reconceive the actual manufacturing process, if it can be harnessed. As a manufacturing interface relative to the architect, it is similar to simple laser/plasma cutting as well as CNC milling. They are all methods by which a digital model is "sliced" into a long series of tool paths for a "robotically" controlled arm (with attached extruder, laser, router, etc.). The technology has expanded into a broad spectrum of robot-driven or robot-assisted processes that move far past the single action of the extruder or laser. These technologies allow computers to directly interface with a "printhead" to output digital form "directly" from the computer (making it more similar to a printer, and hence its name). The revolution taking place (albeit more slowly than former President Obama likely anticipated) is transforming the way in which we manufacture – from repeatable parts to what is often termed "mass customization" or automation. Mass customization or automation potentially allows the manufacture of, say, 600 distinct components at the economic equivalent to designing and manufacturing only one part 600 times. This opens the door to a much larger degree of design complexity than previously imagined.

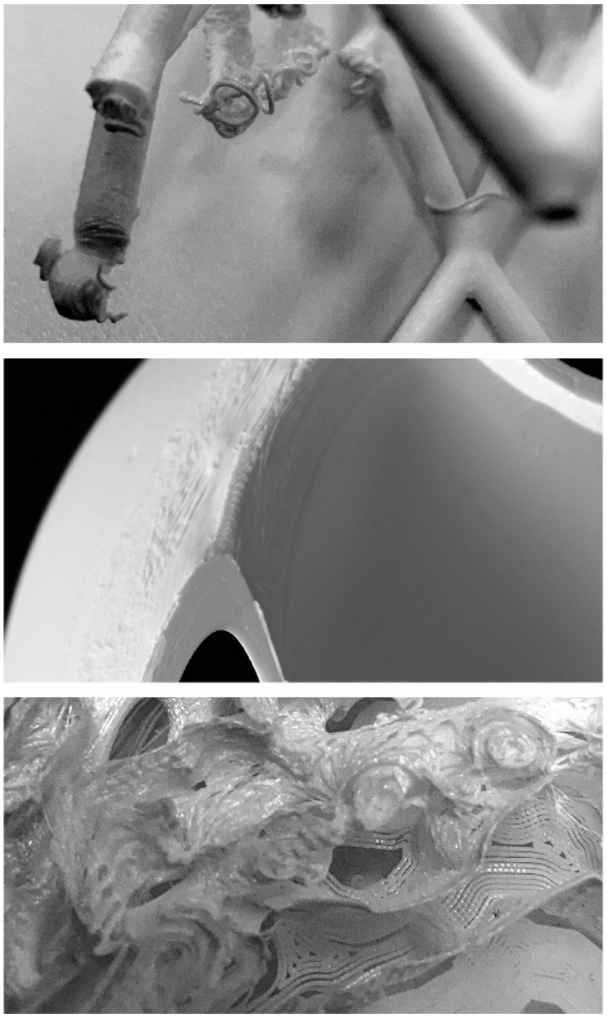

Figure 2. Examples of the adversarial nature of PLA typical to small-scale 3D-printing: extruder speed/pressure issues (top), unsupported overhangs (middle), extruder temperature issues (bottom).

The challenge with this technology is that the material properties of the manufactured parts are quite dependent on their output (the viscosity of the concrete through a given extruder for instance). Also, because the material properties are so specific to their method of output, the typical vagaries of any material are even less predictable in this environment. (Fig. 2)

Digital Fabrication as Research

Because, or due to, material complexity and its inherently symbiotic relationship to its method of manufacture, the schools pioneering the research into large-scale additive manufacturing are typically already well tied to their engineering counterparts, often housed within the "polytechnic" model. For this paper, we will only consider a few schools at the forefront of the research into this technology to focus on their integration within the typical architecture curriculum.

The ETH Zurich's Department of Architecture is rooted in a material understanding of architecture, based in part on its founder, Gottfried Semper.[16] The school itself is founded in the understanding of the polytechnic and is embedded in the way they describe their own teaching model, "The teaching of design and construction draws its central impulses from building praxis as well as in-house research."[17] Because the ETH Zurich is highly research-focused, and in part because it is the dominant university of a small wealthy nation, the University promotes what they call National Centers of Competence in Research – interdisciplinary hubs where research can coalesce.[18] DFAB, the Digital Fabrication Research Center and the ITA, the Institute of Technology in Architecture (run by Gramazio-Kohler), are both tied to the National Center of Competence in Research Digital Fabrication as well as the Department of Architecture, and they are fiscally supported at the national level. DFAB and ITA are primarily focused on their research output. There are many professorships tied to both DFAB and ITA, and the research is embedded in the University, but the professors typically do not teach within the studio-based curriculum (what in the United States would typically be the foundation for a NAAB-accredited degree in architecture), they are part of a Master's of Advanced Studies program or supporting lecture course.[19]

Similarly, the University of Stuttgart has an Architecture and Planning faculty that are divided into several institutes. Their Institute of Computational Design (ICD, led by Achim Menges[20]) is another interdisciplinary research hub, often collaborating with the Institute for Building Structures and Structural Design (led by Jan Kippers). Similar to the ETH's Master of Advanced Studies, Stuttgart has a two-year Master of Science in integrative technologies and architectural design research. The research and programmes created around digital fabrication are not tied to the studio-based curriculum.

Stuttgart and the ETH's research into Digital Fabrication – the material science, engineering, technology – is consistently pioneering the frontier of the capabilities and possibilities of this technology. The ETH, because of its national support, has strong ties to Swiss manufacturing, and the infrastructure for both programs is in itself unusual, promoting the level of collaboration necessary to push this technology forward.

MIT's School of Architecture and Planning is historically more tied to the "polytechnic" architecture school model. Similar to Stuttgart and the ETH, the school has "groups" and "labs," subdivisions of key faculty that have a specific research focus. These groups are similarly tied to more advanced or topical degrees that they offer, and the labs are typically primarily supported through corporate sponsorship. For instance, the Self-Assembly Lab, led by Skylar Tibbets, and the Media Lab are challenging the traditional research model by, "focusing on design as a creative driver to blend basic and applied research and, at the same time diversify application, collaborations, and funding opportunities."[21] Their research model is akin to the ETH's Centers of Competence. They use a combination of industrial and government funding, are primarily interdisciplinary, and are tied to the university curriculum through Phd research and graduate assistants, not as an integrated part of the architecture curriculum.

Unfortunately, while the research from these universities is cutting edge, it does not translate into their traditional architecture curriculums in a more wholesale way. The building technology they are pioneering is not integrated into the curriculum generating the future architects. Students, unless they are motivated and able to pay for an additional degree, are not tasked to test the limits of that technology. It is confined to the "advanced" topical study, something aside from the traditional path a student would take to become an architect. The challenge with these programs is how to translate this hybrid research model into an architecture school where a typical design-build studio might reside.

The Bartlett School in the University College London (UCL) and Sci-Arc in California offer an avenue into how this technology – its potential and limitations - might be explored within the studio curriculum. The Bartlett, entrenched in the English model of architecture schools, is primarily focused on training through apprenticeship. How this has translated into the university model is through a series of year outs, where students learn (primarily through tutors, who are typically practicing architects) in the university setting, intern to apply those skills, and then return to the university for additional study. Their work becomes increasingly self-driven, so that by the third year, students are generating their own research-driven projects (with tutelage), culminating in a final research proposal for their fifth year of combined research and internship.[22] The student/faculty research is deeply entwined and fundamentally tied to the studio curriculum. Similar to MIT, Stuttgart, and the ETH, the Bartlett offers several topical study programmes where the research may be more specifically focused (the Design Computation Lab, DCL, and Interactive Architecture Lab, IAL, at the Bartlett is linked to these programmes, from which much of their research is emerging).[23]

Bob Sheil (current director at the Bartlett) and Ruairi Glynn (director of the Interactive Architecture Lab at the Bartlett) have been pivotal in putting the Bartlett at the forefront of research into digital fabrication, helping to launch the FABRICATE conference in 2011, which addressed, "…prevailing shifts in the contemporary production of architecture: physical processes, material systems, machines and the bespoke as well as representation and manufacture."[24] FABRICATE 2011 highlighted the academic- and practiced-based research into "design and digital manufacturing."[25] The school has driven student interest in digital fabrication by bringing professional interests into the school, which has been a part of the school since its founding.

SCI-Arc is a much newer school, founded when it broke with the California State Polytechnic University at Pomona and remains one of the few independent architecture schools in the world.[26] Like the Bartlett, the school is tied to its professional "tutors", or faculty, who are primarily practicing architects. [27] Similar to the Bartlett, the faculty are drawn to the school because it is an environment of experimentation and exploration. Both schools have a strong tradition of material experimentation, or as Applied Studies coordinator Herwig Baumgartner states, "SCI-Arc is and has always been geared towards speculating about the future of design and construction technologies."[28] This forward thinking illuminates why both schools have been quick to integrate digital fabrication and robotics into their curriculums.

Additive Manufacturing as Design-Build Studio

These universities' approaches to additive manufacturing (as opposed to the 3D printer as model maker) place the adversarial role of materials at the center of their research. They are producing real projects at full scale that are looking at what the technology is capable of, through the reciprocally connected material means. The DFAB House at the ETH[29] is a built prototype that continues to literally grow out of the research at the school. Achim Menges's work with the ICD has a growing list of built installations, where again, they are testing the material limitations alongside its manufacturing technology (including the ICD/ITKE and BUGA Pavilions)[30]. Skylar Tibbets and Neri Oxman at MIT are also producing installations, inventing the materials they are working with (Oxman's work with chitosan in the Ocean Pavilion[31] and Tibbets' work with Steelcase deploying "rapid liquid printing"[32] with polyurethane are both good examples). Their research is pushing the manufacturing technology forward, alongside the materials they are working with. What is challenging about their work is that it does not present an easily integrable model for how this research could be brought into the traditional studio, particularly design-build studio, setting.

Despite this quandary, there is a pressing need to introduce this method of manufacture/technology as a *construction process* to architecture students. The point is not to encourage the success of large-scale built outcomes, but to expose an entire generation to the manufacturing methods they will confront in the practices they join in the future. Returning to Eidlitz's prompt to always consider how to build a thing first, architects and students of architecture need to absorb construction knowledge in order to design. Robot-assisted manufacturing technologies is at a crossroads. It will either learn to mimic current construction methods, assuming human roles as we have seen take place in shipping distribution and automotive manufacturing. Or, like the schools introduced here, focused research on the reciprocal, adversarial, nature of materials and their method of manufacture will transform the materials we currently work with through Carpo's search-based form finding.

What the Bartlett and SCI-Arc's programs offer, in terms of a more applicable studio model, is a kind of free form-finding not inherently dependent on pure materials science or overly science-based structural calculation. For instance, the DCL's *CurVoxels* project is not exploring an inherently novel material, it is looking at a more novel application of "traditional" polylactic acid (PLA) FDM printing that has been scaled up from the .1-.3mm layer of the typical 3D print to 10-20mm, where a robot arm is "spatially printing,"[33] printing in space rather than through layers. The end goal of the project, while it was a chair, was not to create a line of furniture. It was, "…a series of efficiencies while also enabling complex material organisations."[34] Retsín and Jímenez García, the tutors on the project, were interested in how to reenvision the way 3D printing is performed, to look for novel (and productive) ways in which the process could be rethought with construction in mind. The project, at an achievable scale for a traditional studio, is more akin to the type of design-build studio introduced in this paper – fabrication research.

SCI-Arc's Robot House is another bridge towards a more typical studio environment. Founder Devyn Weiser describes the workflow in House as distinct from a typical shop environment:

"In a shop environment, typically, a student will have a specific task to be executed on a purpose-built machine, eg. laser cutter. In Robot House, workflows may be more spontaneous, with designers collaborating and interacting with machines and materials unexpected outcomes."[35]

Several electives at SCI-Arc integrate the Robot House facilities into their course content, essentially treating the facility as a more typical shop space, again using the robots to explore and test the technology. While not design-build in the more professional practice or abstract material research model, the House promotes the technology as an integral part of the curriculum.

When design-build is more focused on fabrication research – "free-form" experimentation through specific materials and processes – it offers a "sandbox" approach to building construction that can easily be applied to more "sophisticated" technology, such as additive manufacturing and other robot-assisted processes. This free-form experimentation can be directly integrated into studio as a part of the design process, as opposed to more pure material science seen in the schools illustrated here. In the studio environment, ideas are not tested against their achievability but on their possibility, and much like Serra's discussion of his process, the technological process is revealed, becoming integral to the design itself. The Bartlett and SCI-Arc serve as examples in this paper, and this type of integration into the studio is slowly emerging in many schools across the country. The challenge on the other end of the spectrum of these schools is how to promote not only experimentation, but also both a criticality and applicability that can translate into the industry. While many schools may not be able to afford a large-scale Kuka robot arm, 3D-printing, even the small-scale printers that are already incorporated into so many architectural schools, can be re-conceived as similar to the drill press and table saw, rather than the laser cutter. While the translation to large scale may not be feasible, the 3D printer can be a window into the construction process.

Notes:

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[10] Leopold Eidlitz, *The Nature and Function of Art, More Especially of Architecture* (New York: De Capo Press, 1977 (orig. pub. 1881)), 479.

[11] *Ibid*, 481.

[12] See Section 5.2 of the Owner/Architect Master Agreement for the language. Section 8.4 of the AIA Master Owner/Contractor Agreement specifically states, "The Architect will not have control over, charge of, or responsibility for, the construction means, methods, techniques, sequences or procedures, or for safety precautions and programs in connection with the Work, since these are solely the Contractor's rights and responsibilities under the Contract Documents." *AIA Document A121 – 2018,* https://contractdocs.aia.org/PreviewFiles/Preview_A121-2018.pdf.

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