Space Resources Roundtable

SRR 2026

Leveraging Established Principles for Landing and Launching Pad Design

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***Resilience Thrust*: Architecture and Design**

- Choose design features and tools to be safe and resilient

***Awareness Thrust*: Detection+Diagnosis+Decision**

- Detect damage and disruptions, diagnose, support decision-making

***Robotics Thrust*: Extend the Range of Actions**

- Increase scope of interventions that can be carried out autonomously

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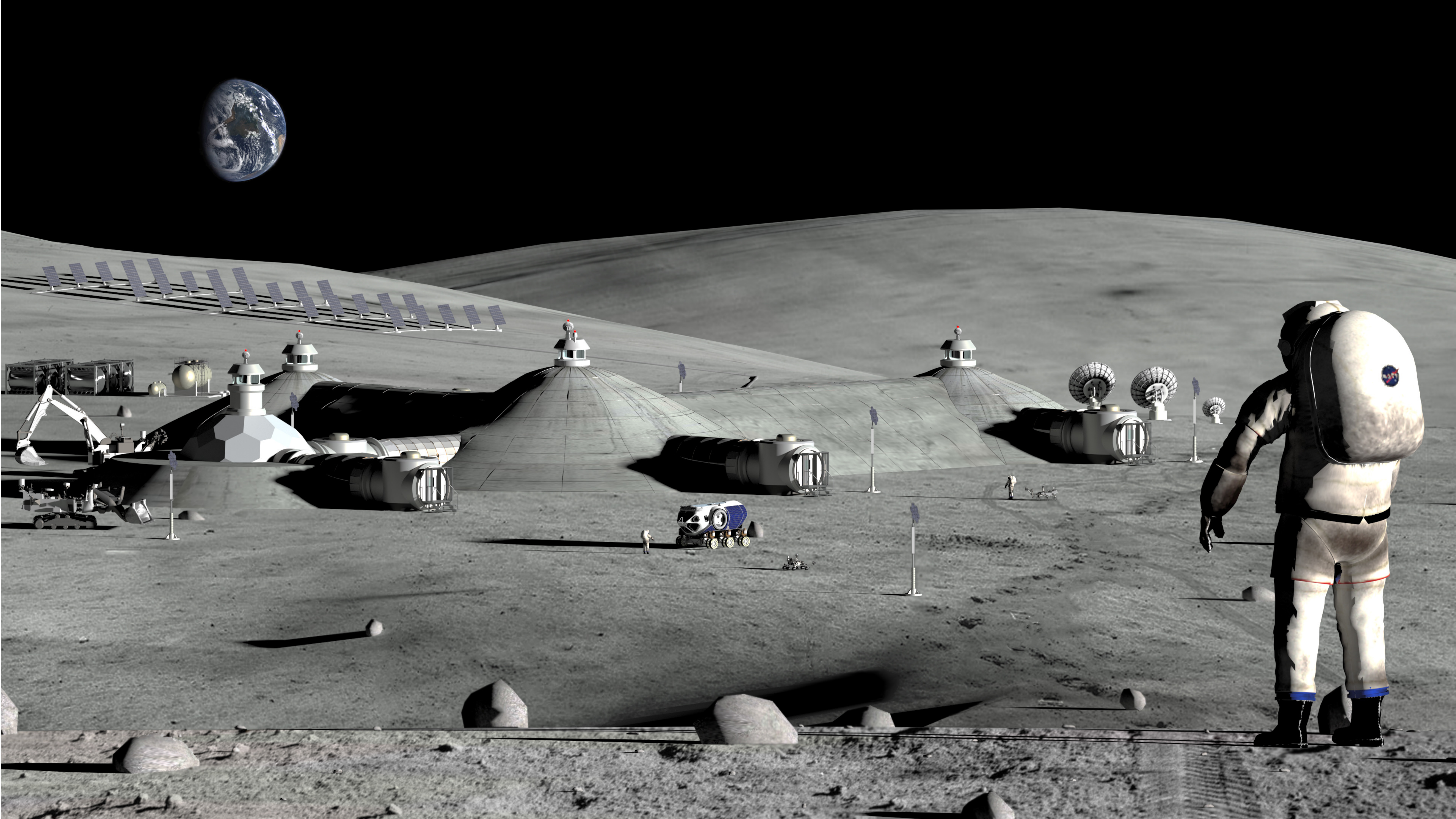
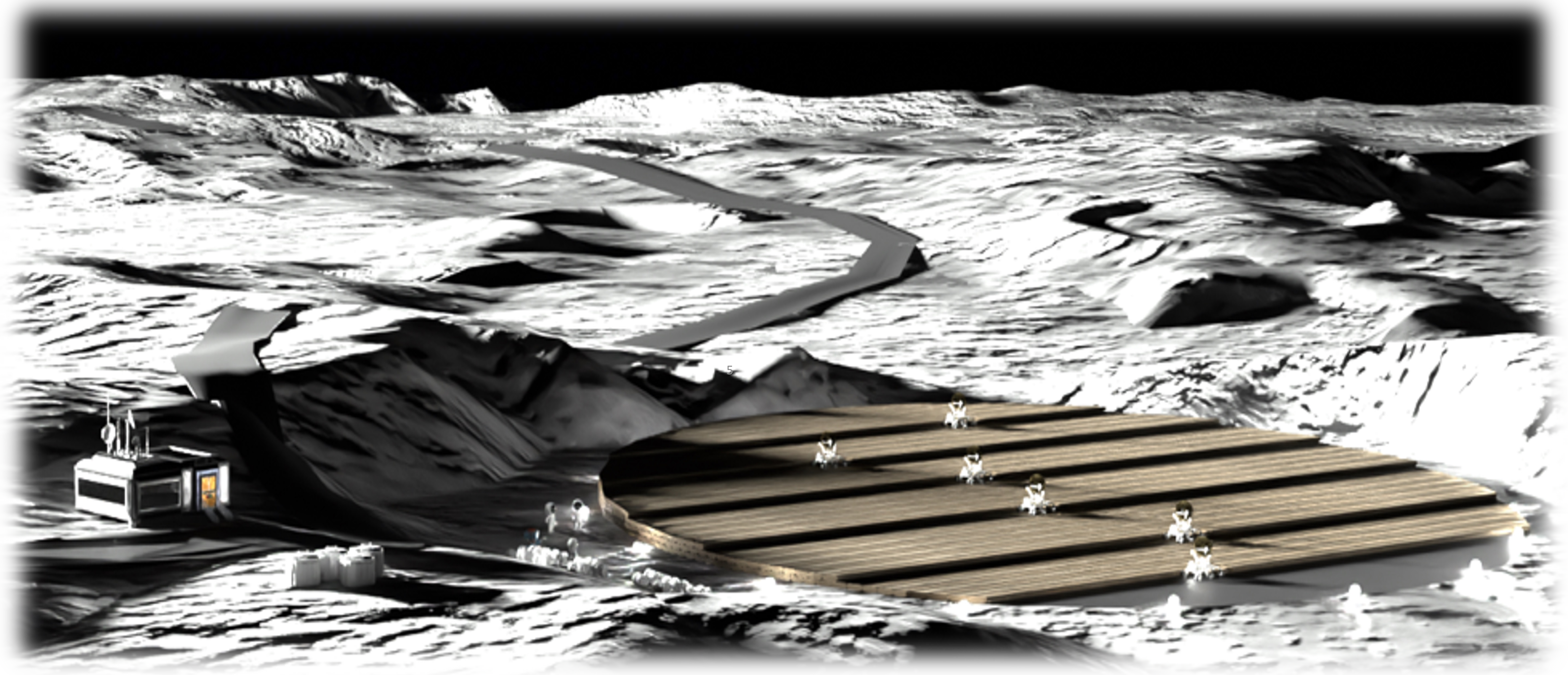


What type and under what conditions and with what consequences is a failure acceptable?

What is **the acceptable probability of failure or appropriate level/margin of safety**?

What is the desired performance (*i.e.*, degree/rate of deterioration, maximum deformations)?

Cr: Oscar Forero



Outline

- Engineering Lunar Structures – a Gap in Knowledge
- Standards:
  - Why we need them? How do we use them?
- "Architectural" Data Gaps to Address
  - To reduce cost, increase reliability
- Case Study:
  - Design of a Launch and Landing Pad
- Closing Comments

Acta Astronautica 240 (2026) 165–182

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Lunar landing and launching pad design considerations using ISRU materials

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ARTICLE INFO

Keywords:
Infrastructure
Landing pad
ISRU
Lunar construction

ABSTRACT

Launching and landing pads (LLPs) will be essential elements to serve a future lunar base. There is widespread acceptance that these structures will be manufactured from in situ materials. Structural materials made from these indigenous materials are expected to be brittle. Thus, they will exhibit the typical diverse behaviors and inherent variabilities in properties that are common in indigenous construction materials. Hard-won lessons on how to design reliable structures from brittle materials on the Earth need to be leveraged. It should be noted that earlier examples of these applications resulted in massive structures. It was not until Portland cements, other cementitious materials, chemical admixtures, steel, and more recently carbon fiber-based elements became available, and in general, composites were better understood, that more elegant and slender structures were realized. In this research, we adapt and apply well-established methodologies used for slab-on-grade construction toward the development of a design framework for lunar LLPs. The structural considerations in designing such a slab are discussed in detail starting from first principles and unknown initial dimensions to illustrate their impact on the design. This approach is necessary given the low state of entropy of the knowledge with respect to performance and actual material properties in such extreme environments. It is demonstrated through an illustrative example in which we design an LLP using the best available information and properties for sintered lunar regolith. Additional information that will need to be obtained or verified through in situ testing is also defined. The example design is intended to service spacecraft of up to 50 tons. The dimensions used for the loads represent spacecraft being developed at the present time for transporting cargo and supplies to the surface of the Moon. The application of a wealth of fundamental knowledge, practical experience, and technologies will be essential for the design and construction of resilient and sustainable infrastructure on the Moon and other similarly challenging environments. The paper concludes with a discussion of the path forward to design and realize such construction on the Moon.

1. Introduction

NASA and its partner agencies have the goal of expanding U.S. human space flight operations to the Moon and supporting a sustained human presence [1]. A critical aspect of both exploring the Moon and developing a sustainable lunar economy is having the necessary infrastructure to ensure reliable, safe, and consistent delivery of equipment and consumables to the lunar surface, as well as launching payloads and crew to lunar orbits [2]. Constructing the right type of infrastructure would enable repeated landings and launches of a variety of spacecraft with different payload sizes [3,4] while supporting the objective to perform precision landing [5]. Ideally, all this activity will take place without significant damage to the LLP, or to any other infrastructure on the lunar surface or in cislunar space.

On the Earth, landing and launch pads have traditionally been monolithic structures. These structures are designed to withstand enormous forces and extreme temperatures, and are subjected to chemicals and other spills that may harm or weaken that structure over time. This type of construction is possible because we have well over one-hundred years of experience with an indigenous composite material, reinforced concrete. Engineers, using concrete in combination with steel reinforcement, have constructed some of the world's tallest and

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https://doi.org/10.1016/j.actaastro.2025.11.071
Received 25 June 2025; Received in revised form 5 November 2025; Accepted 27 November 2025
Available online 2 December 2025

Mount, et al., (2025) "Lunar Landing and Launching Pad Design Considerations Using ISRU Materials," *Acta Astronautica*, (240) pp. 165-182, https://doi.org/10.1016/j.actaastro.2025.11.071.

Engineering Lunar Structures – a Gap in Knowledge

The engineering of reusable and resilient lunar structures is a critical element toward achieving the ambitious Moon base plans.

- The surface of the Moon is more extreme than anywhere on Earth.
- Solicitations (environment and loads) include:
  - Temperature extremes / Temperature gradients
  - Hard Vacuum / Pressure differentials
  - Abrasive Dust
  - Micrometeoroids
  - Radiation
  - Gravity
  - Moonquakes

- We need to know much more about these solicitations to design structures.

Engineering Lunar Structures – a Gap in Knowledge

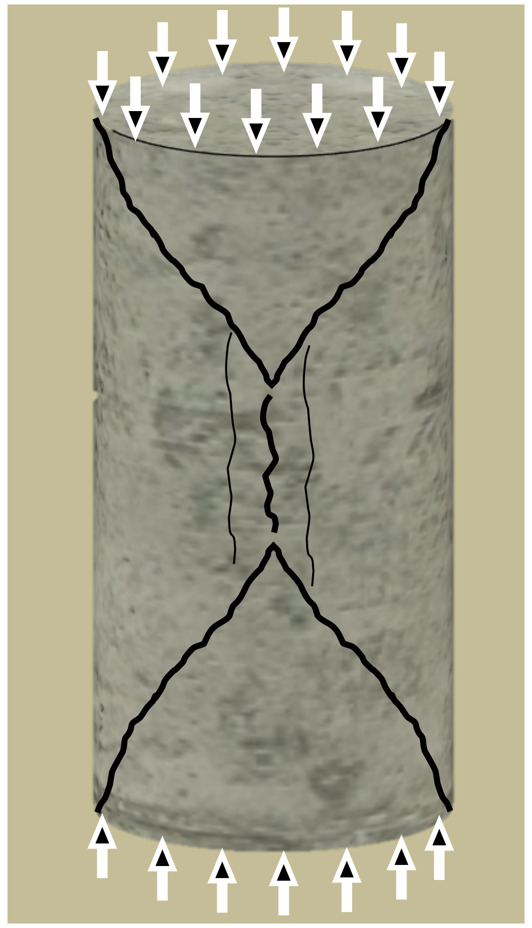
- Regolith-based materials, are being proposed for construction on the Moon.
  - Pros include reduced cost of transporting large amounts of materials or prefabricated elements, instead relying on just transporting equipment
  - Cons are that materials that are made, all or in part, from indigenous Lunar materials are likely to have wide variability based on the make-up of the material, location where it was taken from, production processes, and time

For design, engineers need dependable information about both the solicitations and the materials for the design of safe, reliable and durable structures from these materials. Simulants are not reliable for this purpose – in situ measurements are needed.

Concrete

- Brittle
- Weak in tension, strong in compression
- Thermal – good insulator, degradation expected
- Variability in strength due to preparation, regional differences, etc

What scale?



Compressive Test

Regolith-based structural materials

- Assumed brittle
- Unknown

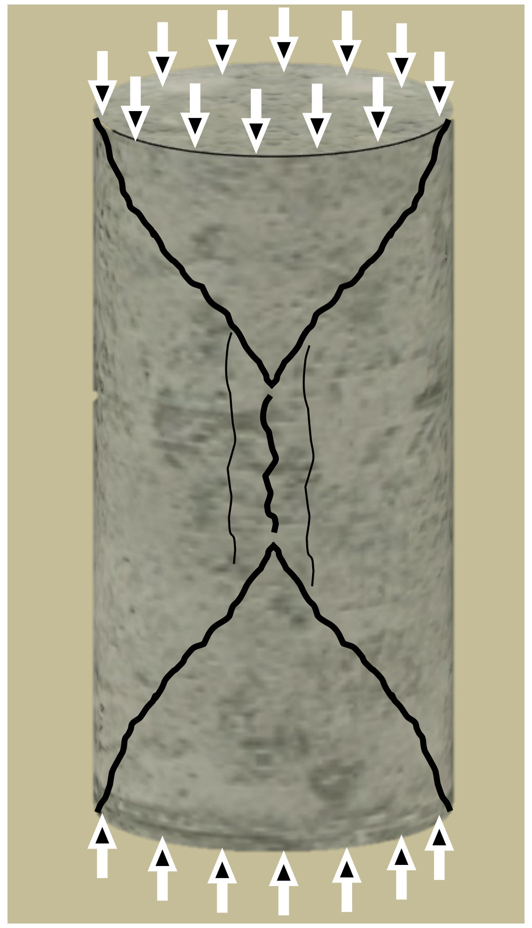
Standard Active | Last Updated: Dec 15, 2023 | Track Document

ASTM C39/C39M-23

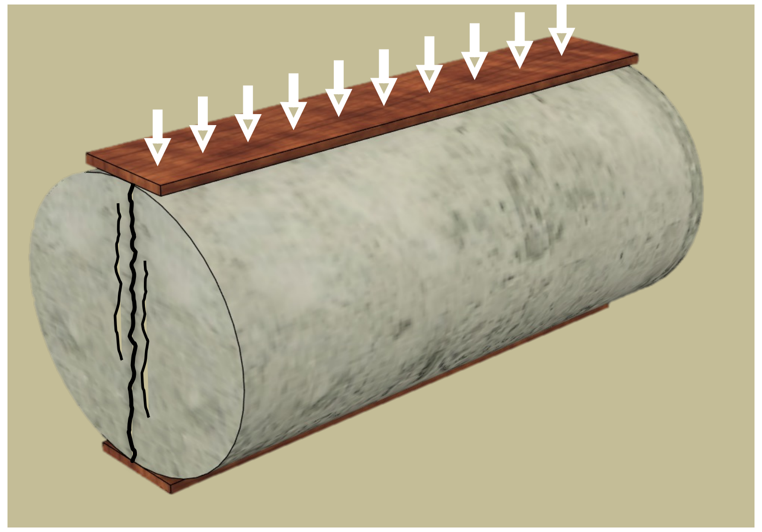
Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens

Standards: ***Why we need them?***
How do we use them?

- A standard is a guideline to perform a type of test, ensuring testing is performed on a uniform and consistent basis.
- Several types of standards will be necessary for building safe and durable structures to serve as habitats, shelters, foundations, launch pads, blast shields, and possibly roadways.



Compressive Test



Split Tensile Test

Standards: ***Why we need them?***
How do we use them?

- Standards will then enable test results that are repeatable and reproducible.

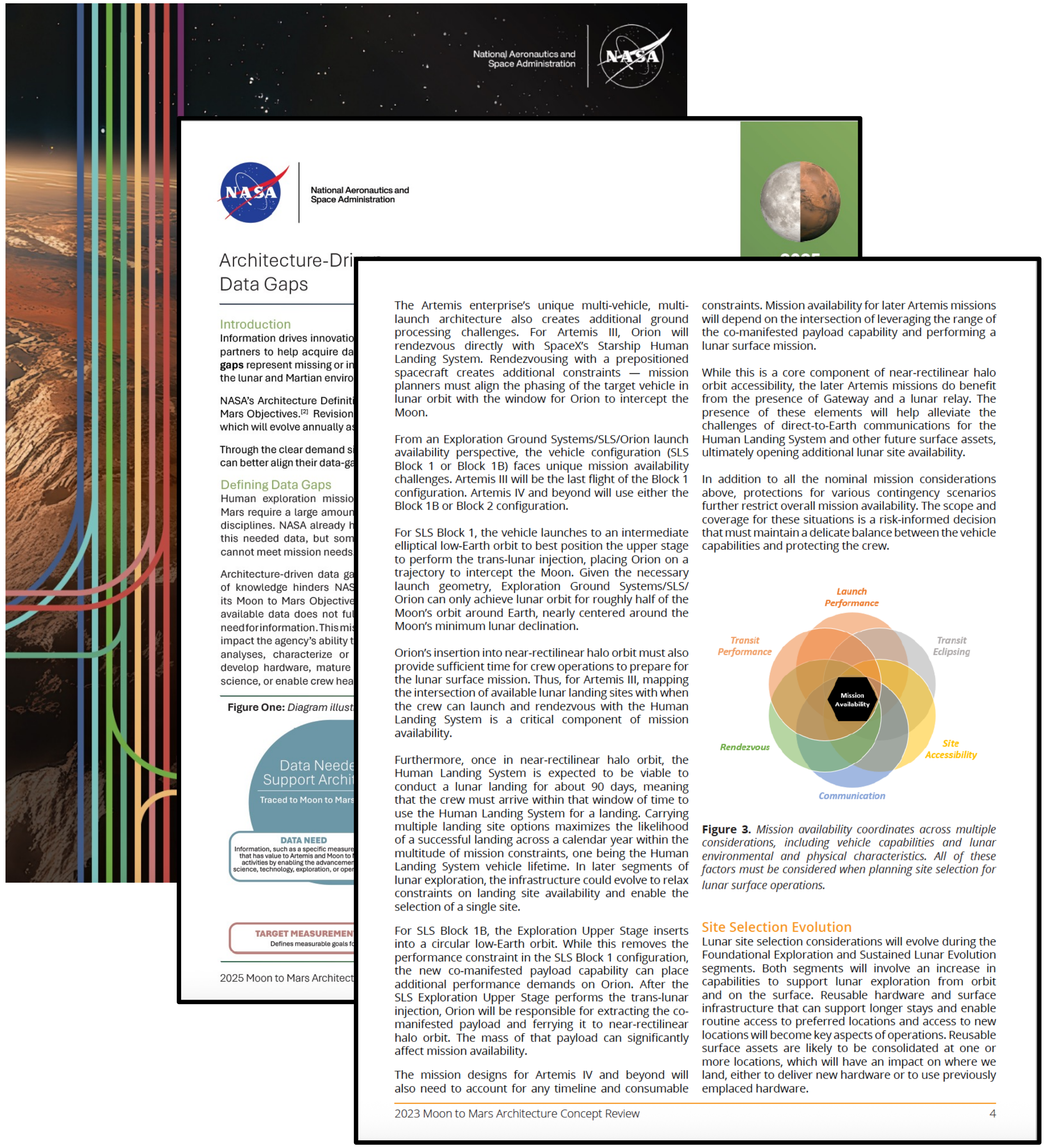
- Allow the engineer to make useful comparisons of test data for design.

- The function of and the solicitations (environment and loadings) on the structure will determine the type of material properties that are needed to inform the design.

Dyke, et al. (2024). “Establishing Standards for Lunar ISRU Structural Materials,” *AIAA Journal*, Vol. 62, No. 7, pp. 2414-2423, https://doi.org/10.2514/1.J063816

Architectural Data Gaps to Address

- Subsurface
- Interface between the Structure and Subsurface
- Manufactured Structural Materials



The Artemis enterprise's unique multi-vehicle, multi-launch architecture also creates additional ground processing challenges. For Artemis III, Orion will rendezvous directly with SpaceX's Starship Human Landing System. Rendezvousing with a prepositioned spacecraft creates additional constraints — mission planners must align the phasing of the target vehicle in lunar orbit with the window for Orion to intercept the Moon.

From an Exploration Ground Systems/SLS/Orion launch availability perspective, the vehicle configuration (SLS Block 1 or Block 1B) faces unique mission availability challenges. Artemis III will be the last flight of the Block 1 configuration. Artemis IV and beyond will use either the Block 1B or Block 2 configuration.

For SLS Block 1, the vehicle launches to an intermediate elliptical low-Earth orbit to best position the upper stage to perform the trans-lunar injection, placing Orion on a trajectory to intercept the Moon. Given the necessary launch geometry, Exploration Ground Systems/SLS/Orion can only achieve lunar orbit for roughly half of the Moon's orbit around Earth, nearly centered around the Moon's minimum lunar declination.

Orion's insertion into near-rectilinear halo orbit must also provide sufficient time for crew operations to prepare for the lunar surface mission. Thus, for Artemis III, mapping the intersection of available lunar landing sites with when the crew can launch and rendezvous with the Human Landing System is a critical component of mission availability.

Furthermore, once in near-rectilinear halo orbit, the Human Landing System is expected to be viable to conduct a lunar landing for about 90 days, meaning that the crew must arrive within that window of time to use the Human Landing System for a landing. Carrying multiple landing site options maximizes the likelihood of a successful landing across a calendar year within the multitude of mission constraints, one being the Human Landing System vehicle lifetime. In later segments of lunar exploration, the infrastructure could evolve to relax constraints on landing site availability and enable the selection of a single site.

For SLS Block 1B, the Exploration Upper Stage inserts into a circular low-Earth orbit. While this removes the performance constraint in the SLS Block 1 configuration, the new co-manifested payload capability can place additional performance demands on Orion. After the SLS Exploration Upper Stage performs the trans-lunar injection, Orion will be responsible for extracting the co-manifested payload and ferrying it to near-rectilinear halo orbit. The mass of that payload can significantly affect mission availability.

The mission designs for Artemis IV and beyond will also need to account for any timeline and consumable constraints. Mission availability for later Artemis missions will depend on the intersection of leveraging the range of the co-manifested payload capability and performing a lunar surface mission.

While this is a core component of near-rectilinear halo orbit accessibility, the later Artemis missions do benefit from the presence of Gateway and a lunar relay. The presence of these elements will help alleviate the challenges of direct-to-Earth communications for the Human Landing System and other future surface assets, ultimately opening additional lunar site availability.

In addition to all the nominal mission considerations above, protections for various contingency scenarios further restrict overall mission availability. The scope and coverage for these situations is a risk-informed decision that must maintain a delicate balance between the vehicle capabilities and protecting the crew.

Figure 3. *Mission availability coordinates across multiple considerations, including vehicle capabilities and lunar environmental and physical characteristics. All of these factors must be considered when planning site selection for lunar surface operations.*

Site Selection Evolution

Lunar site selection considerations will evolve during the Foundational Exploration and Sustained Lunar Evolution segments. Both segments will involve an increase in capabilities to support lunar exploration from orbit and on the surface. Reusable hardware and surface infrastructure that can support longer stays and enable routine access to preferred locations and access to new locations will become key aspects of operations. Reusable surface assets are likely to be consolidated at one or more locations, which will have an impact on where we land, either to deliver new hardware or to use previously emplaced hardware.

2023 Moon to Mars Architecture Concept Review 4

Architectural Data Gaps: Subsurface

- Subsurface is not known to the level of detail needed to inform design
- The behavior of granular materials such as regolith requires in situ measurements and observations
- Need to know, at least:
  - Depth of the regolith
  - Material characteristics (grain size distribution, density, relative density)
  - Mechanical properties as a function of depth
  - Voids or boulders – to determine site preparations

- At this time candidate sites have been identified, but have not examined them to the level of detail needed to consider if they can support a Moon base

Architectural Data Gaps: Interaction Between the Subsurface and Structures

- We know rocket plumes will interact with the structure/soil
- Interactions also occur between the structure and subsurface

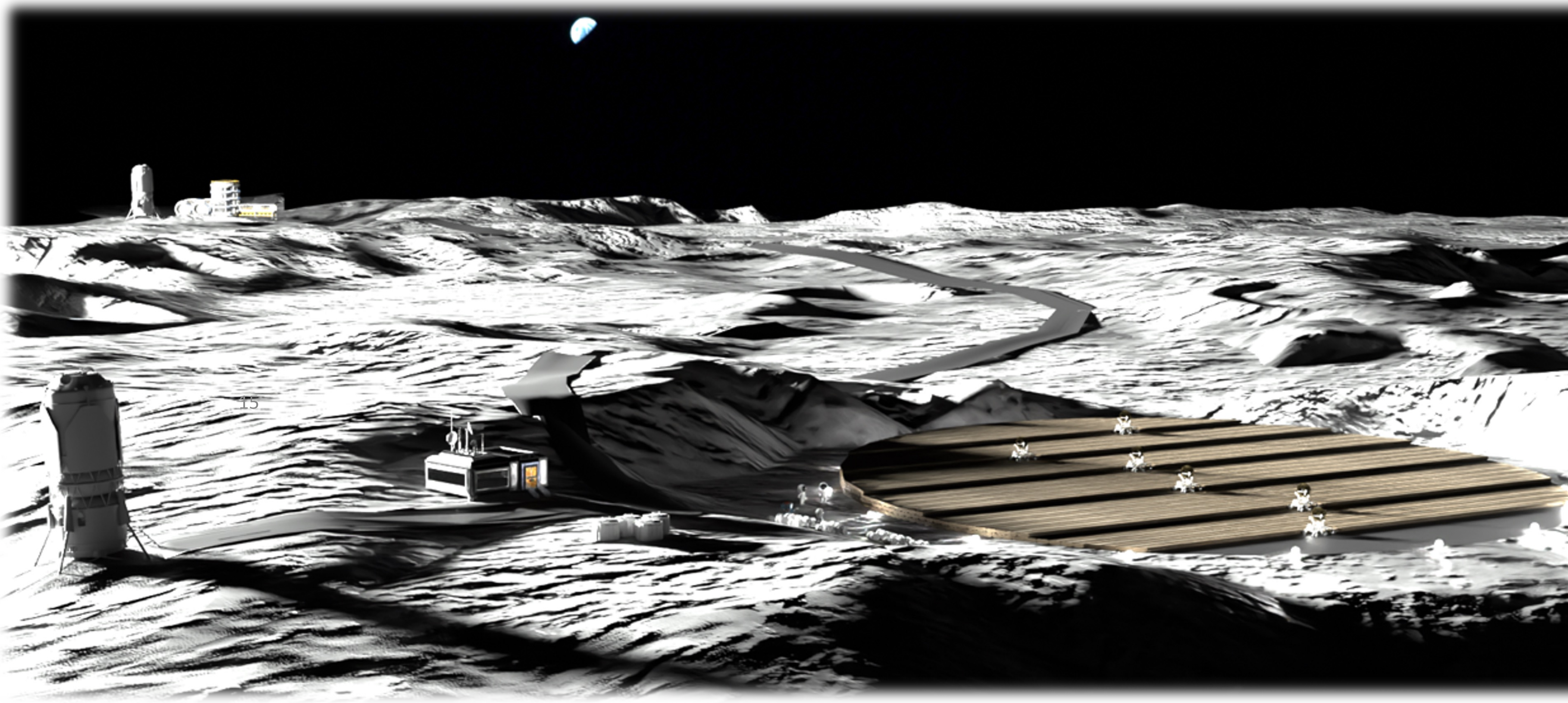
- Friction at the interface between the soil and structure
  - Expand/contract with variation in temperature
  - Causing stresses within the structure that must be quantified

- The structure will compress the soil locally
  - Require a good estimate of the stiffness of the soil and/or the coefficient of subgrade reaction

Architectural Data Gaps: Manufactured Structural Materials

- Manufactured structural materials are expected to:
  - Be brittle
  - Spatial variability

- Need to characterize those materials for:
  - Compressive strength
  - Tensile strength
  - Durability



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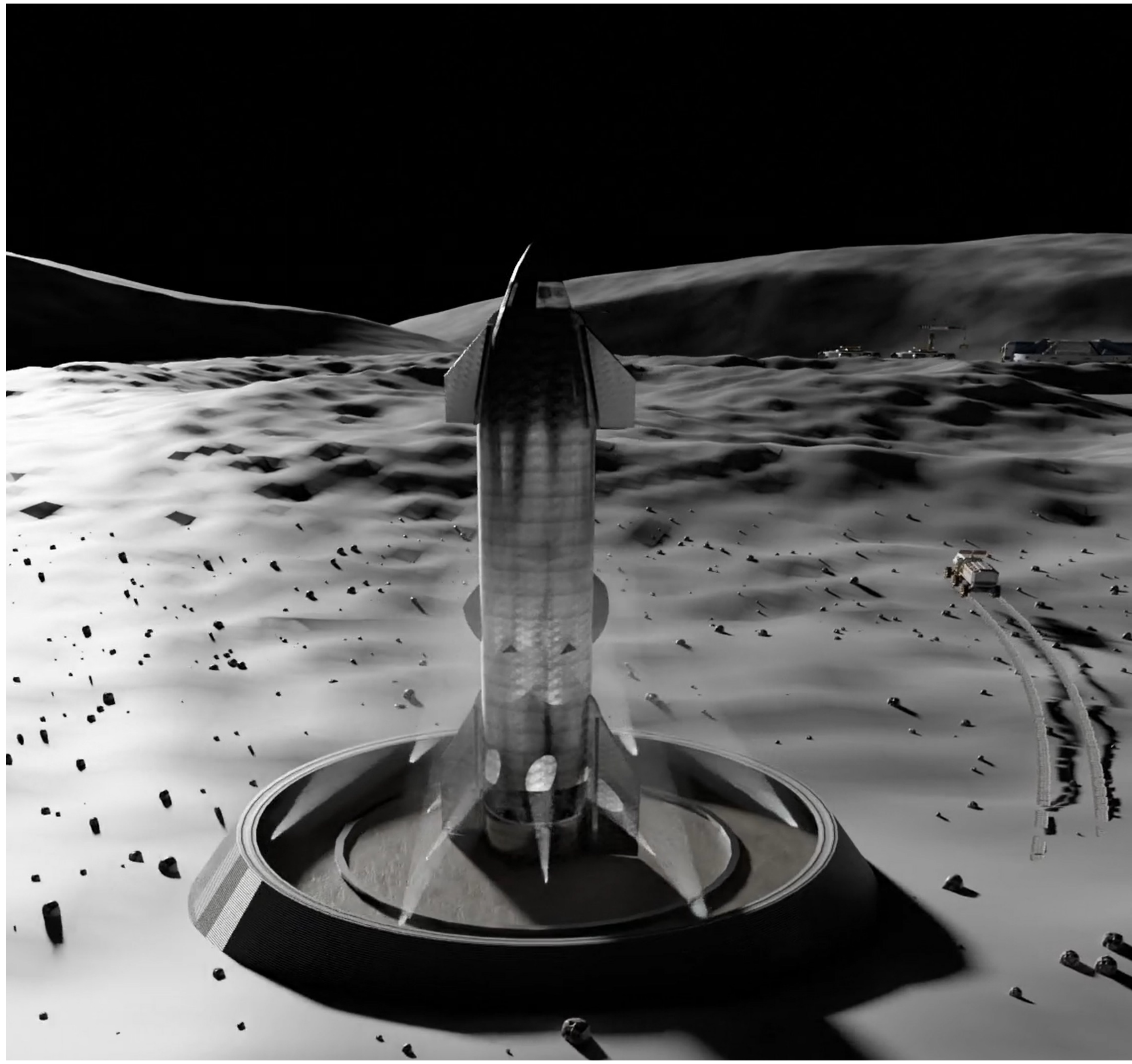
<u>Case Study</u>: Design of a Launch and Landing Pad

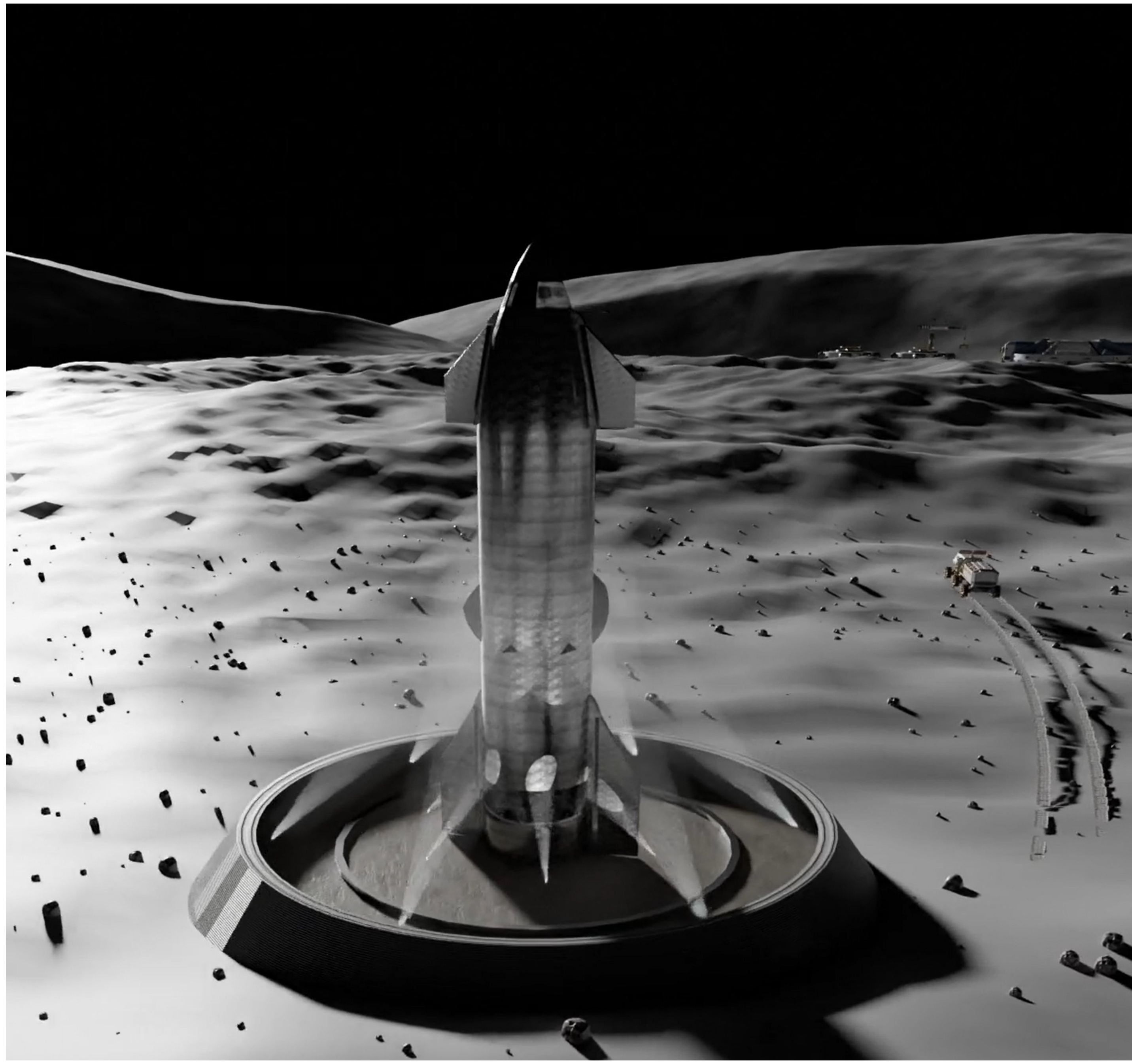


Consider the design of an LLP engineered to resist the impact of a lander

- 50-ton spacecraft
- 30m diameter pad
- 1 m diameter footpad

- <u>First principles approach</u>
- It also makes it possible to illustrate the impact of assumptions on the design outcome

<u>Case Study</u>: Design of a Launch and Landing Pad



- <u>Decisions</u>:
  To make in advance to inform the design:
  - Reliability needed?
  - Reusable?
  - Expected service life, number of landings?
  - How much damage is tolerable?

Case Study: Design of an ISRU Launch and Landing Pad

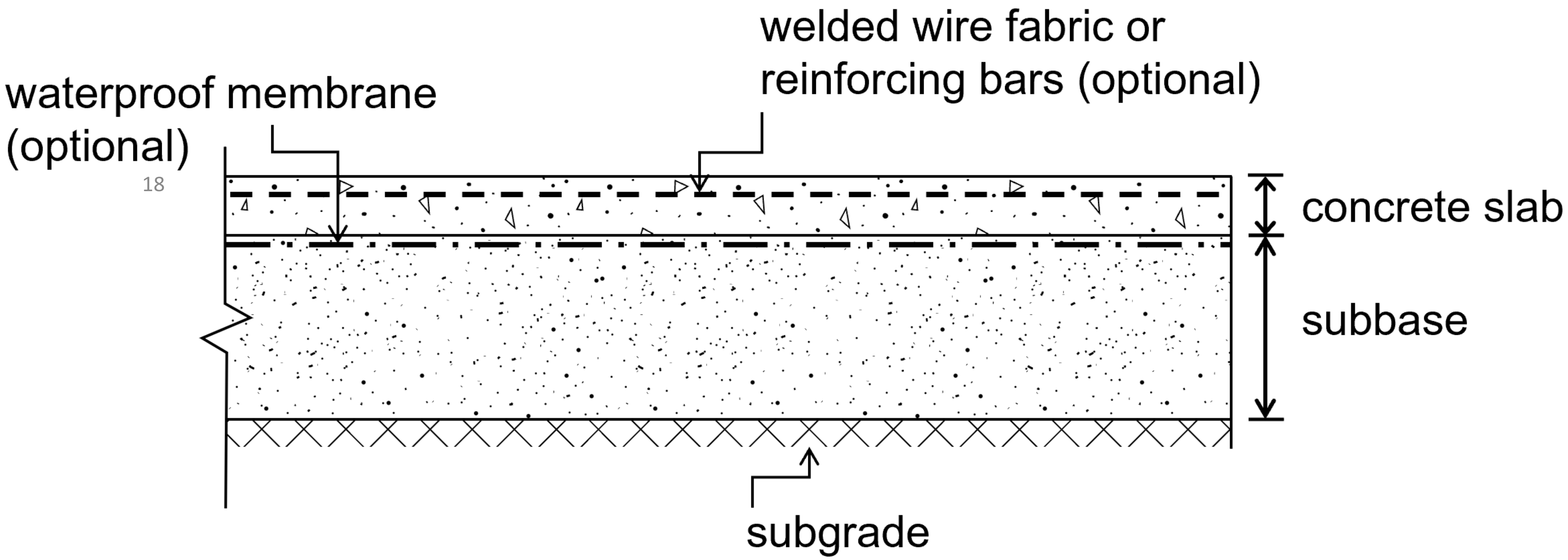
Typical *slab-on-grade construction* (Westergaard, 1926)

Goal: develop and demonstrate a <u>framework</u> suitable for designing an LLP from ISRU materials.

Concrete Slab-on-grade design

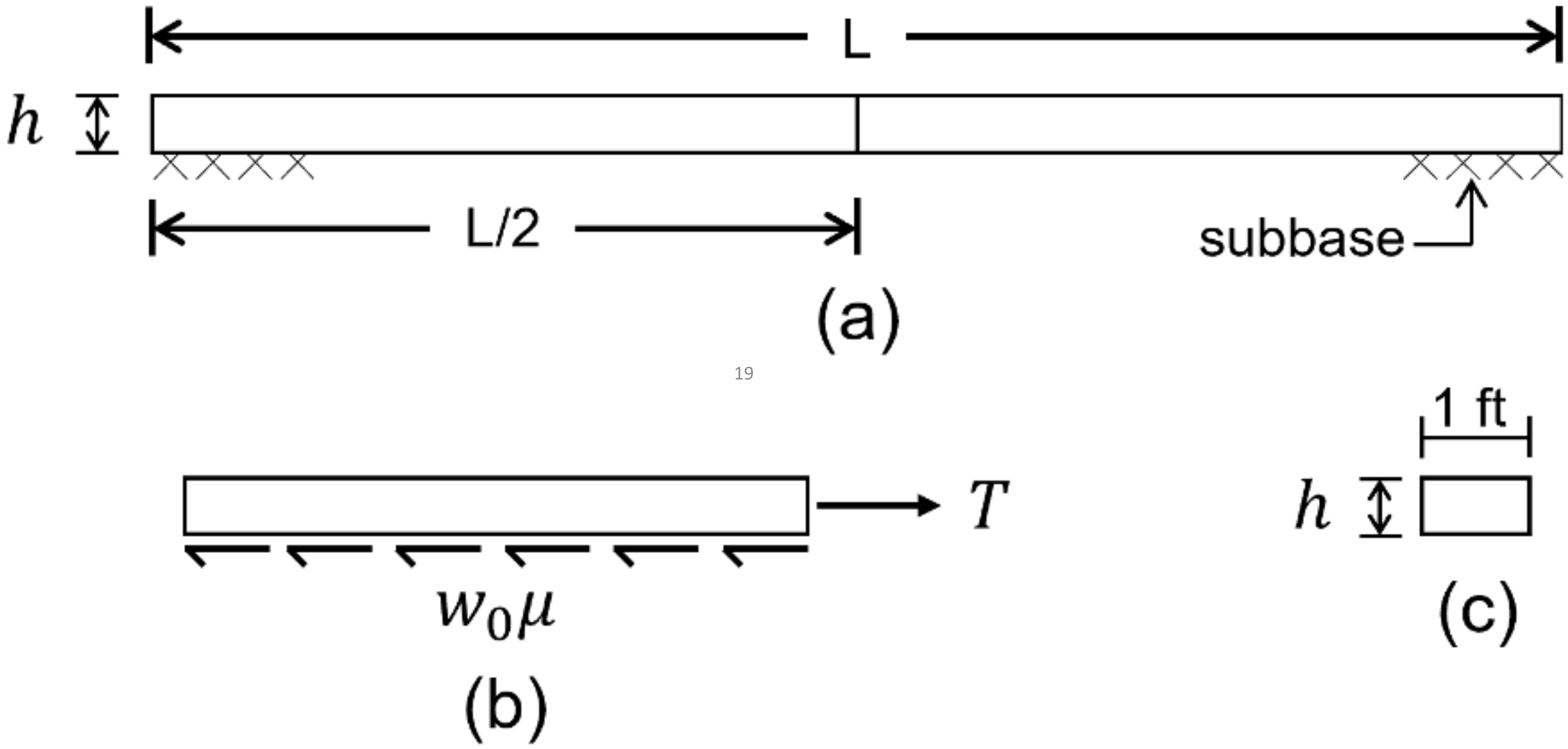
Consider

1. Thermal considerations
2. Heavy concentrated loads
3. Punching shear
4. Rocket plume thermal loads



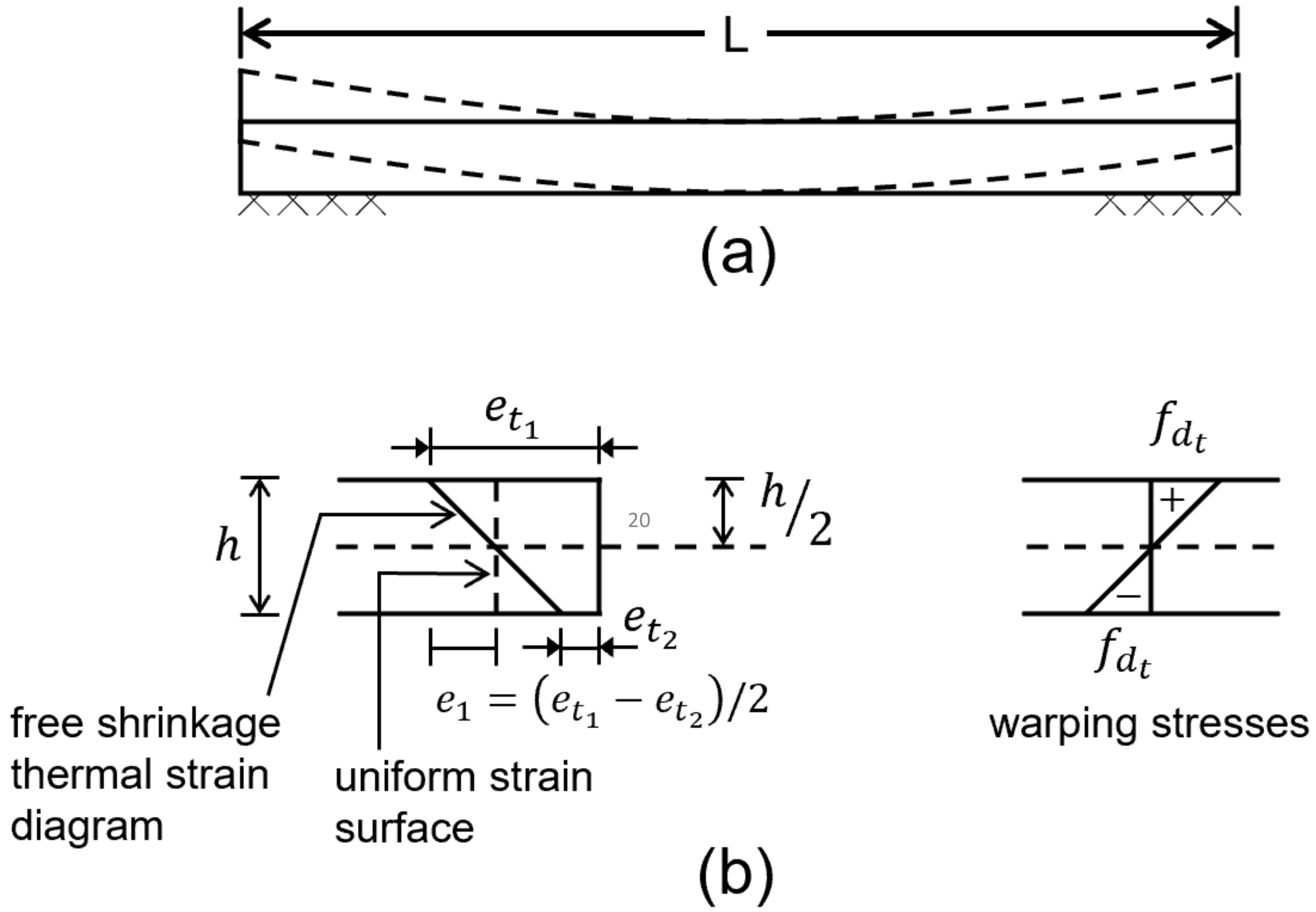
1. Thermal considerations: friction

Subbase drag effect: (a) Slab segment between joints;
(b) Equilibrium of horizontal forces; and (c) Cross-section view

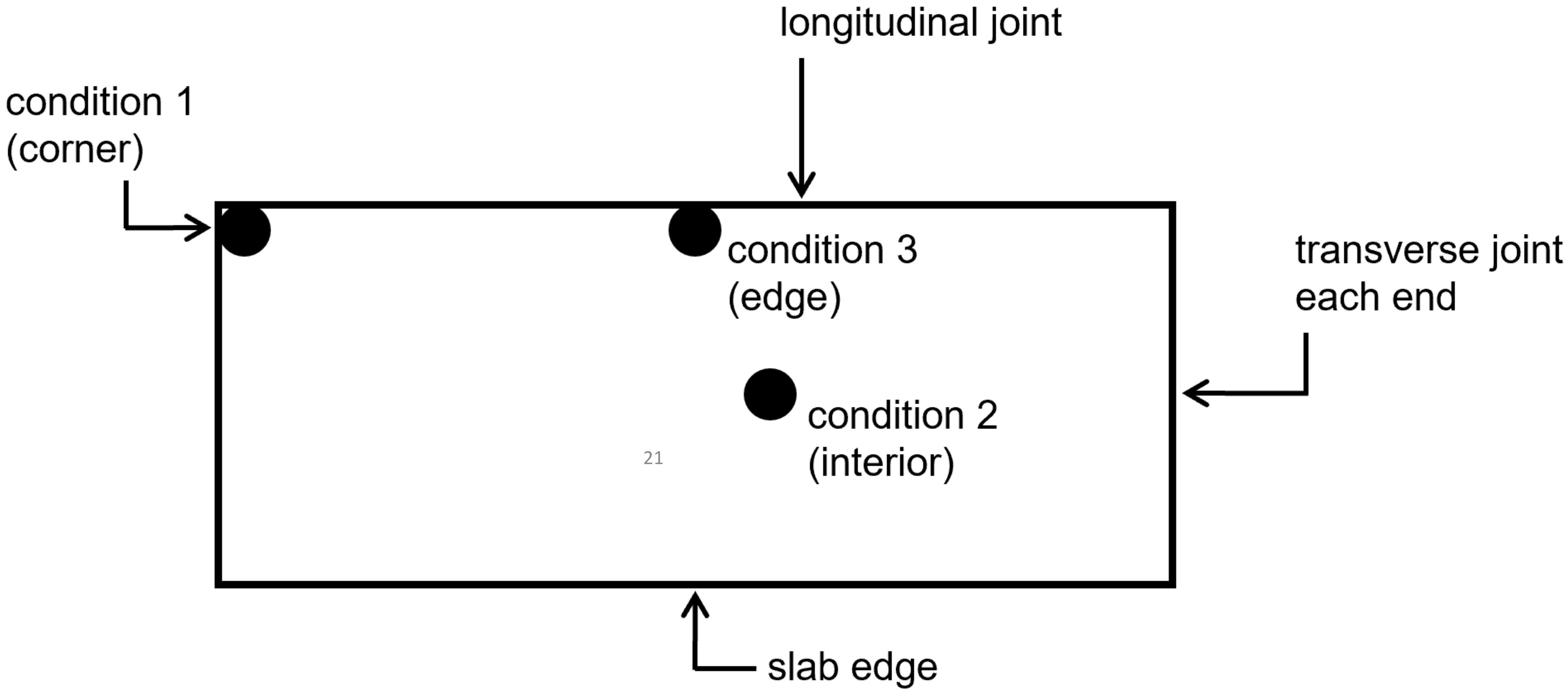


2. Thermal considerations: restrained shrinkage

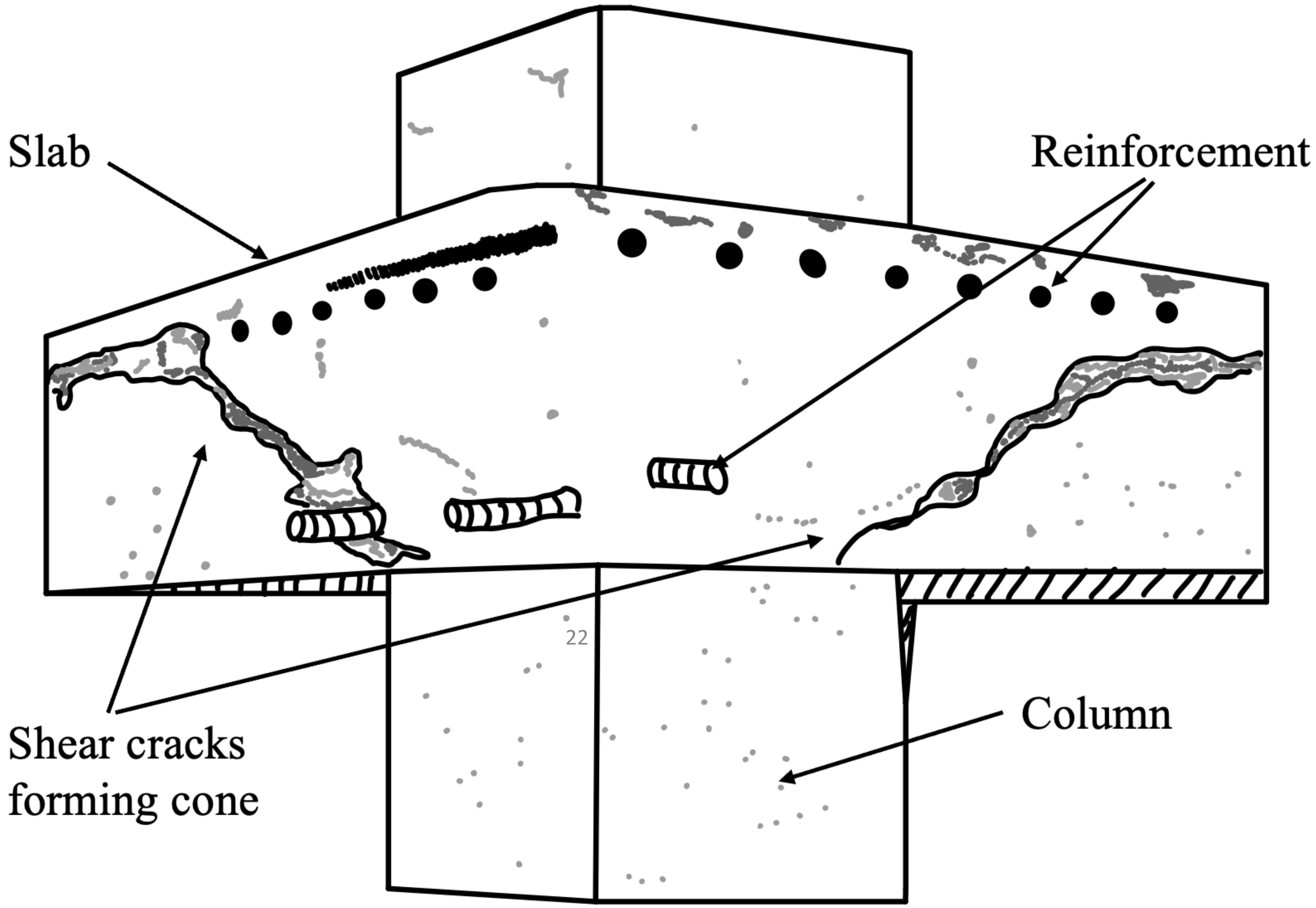
Effect of differential temperature or shrinkage:
(a) Warping of slab; (b) Strains and warping stresses.



2. Heavy Concentrated Loads

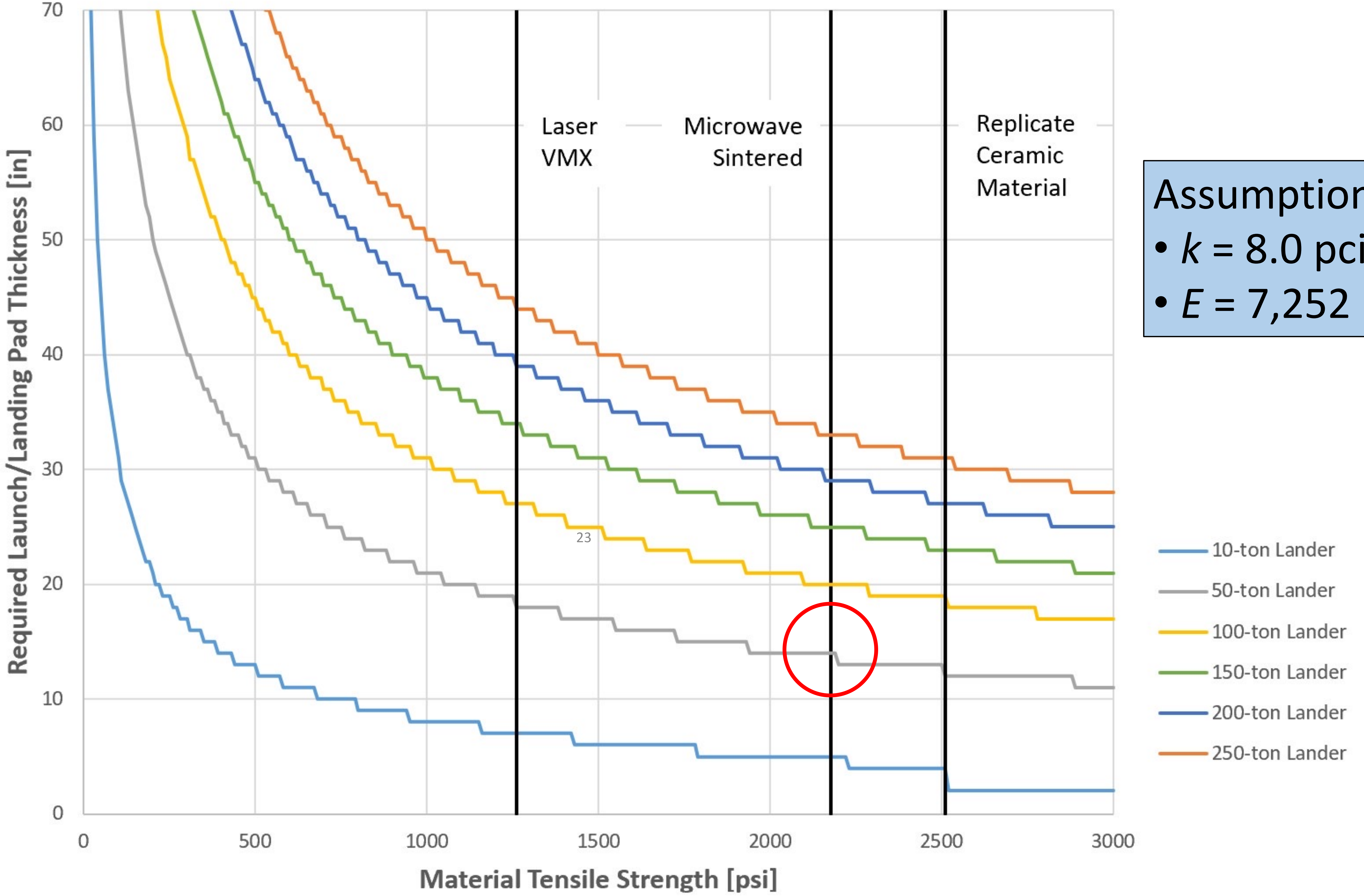


3. Punching shear



Design Results

LLP Thickness – Required to Prevent Flexural Cracking using an allowable stress of 2/3 the tensile strength – to nearest inch

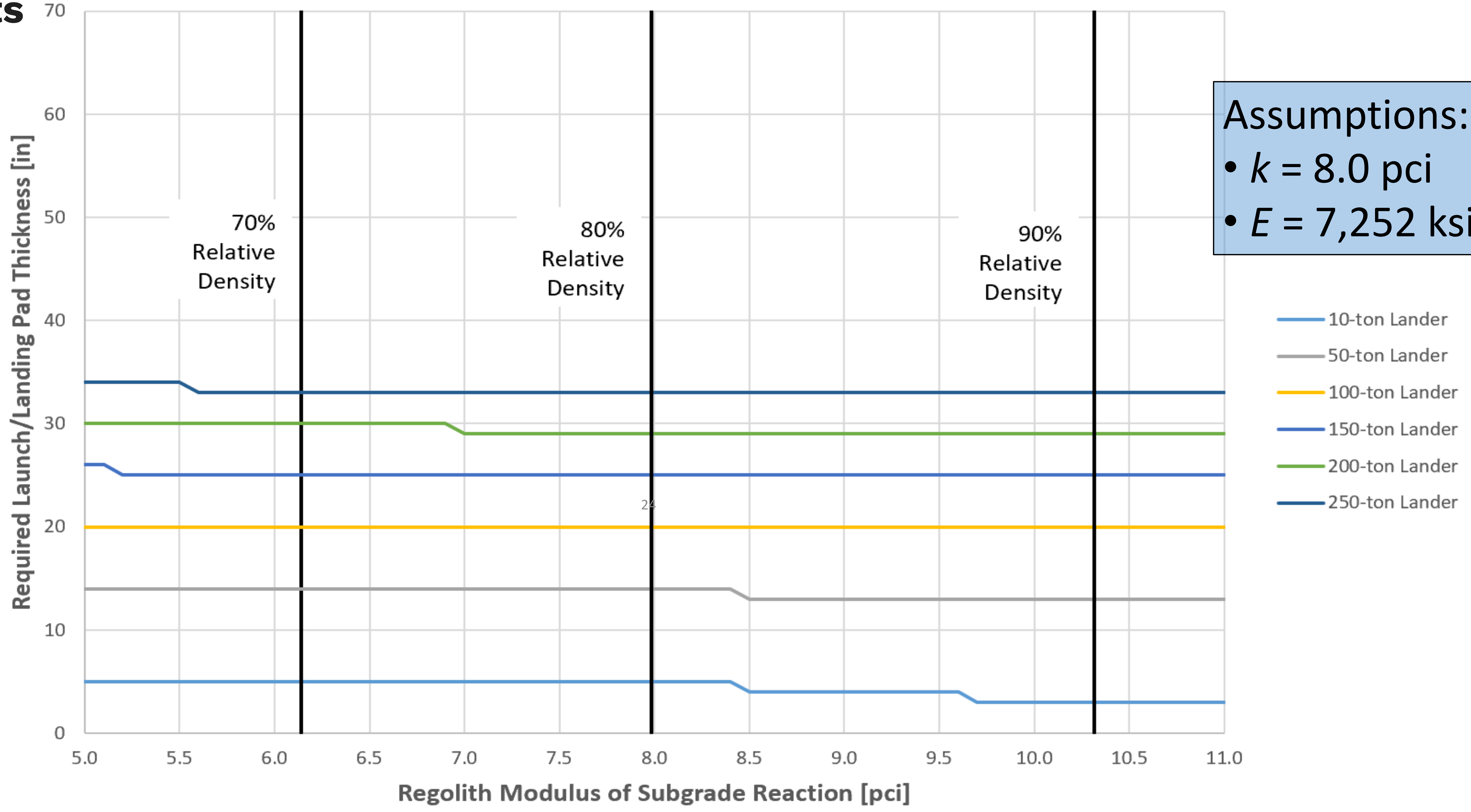


Assumptions:

- k = 8.0 pci
- E = 7,252 ksi

Design Results

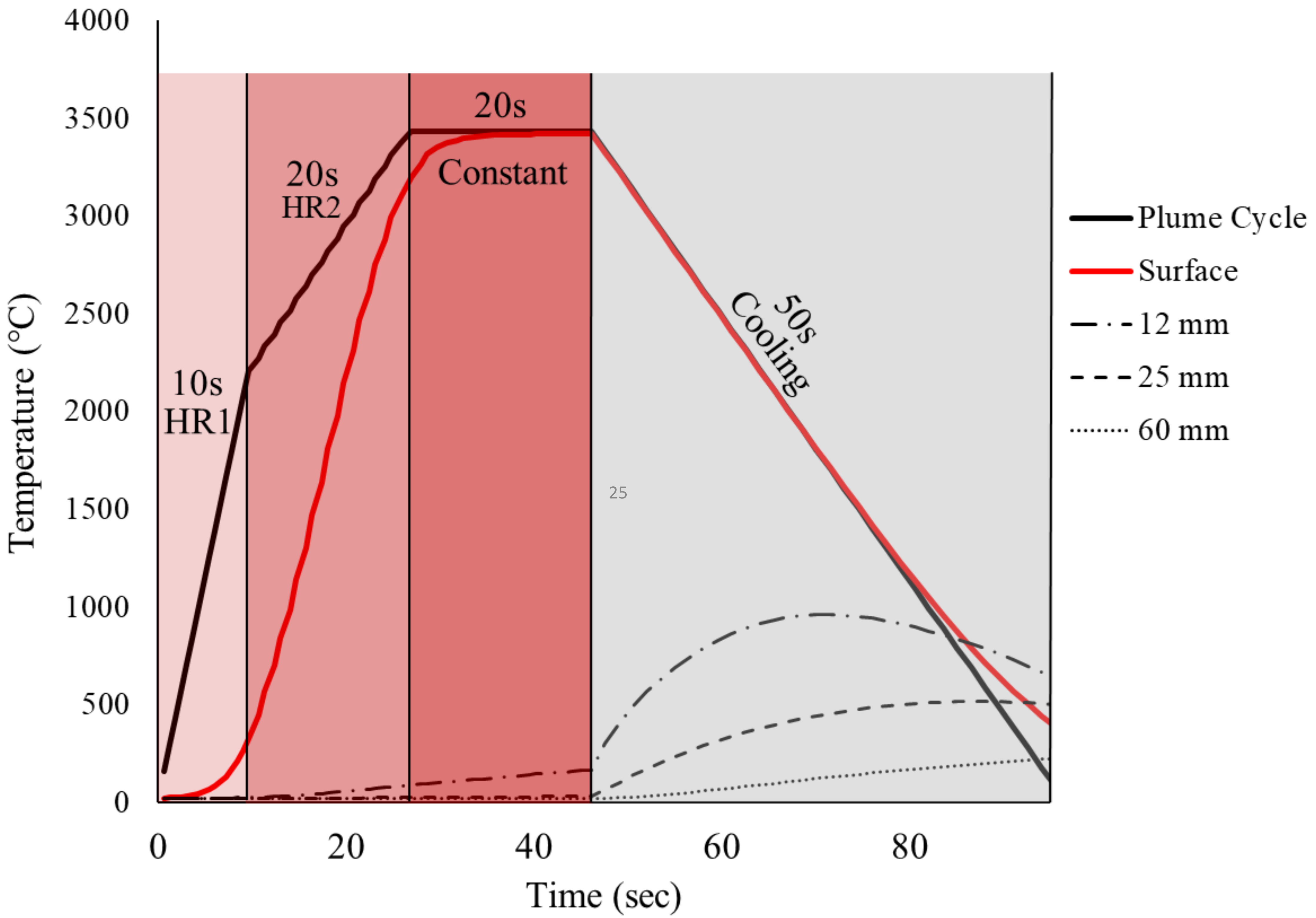
LLP Thickness – Sensitivity to k with Microwave Sintered Material for different levels of compaction



Assumptions:
- *k* = 8.0 pci
- *E* = 7,252 ksi

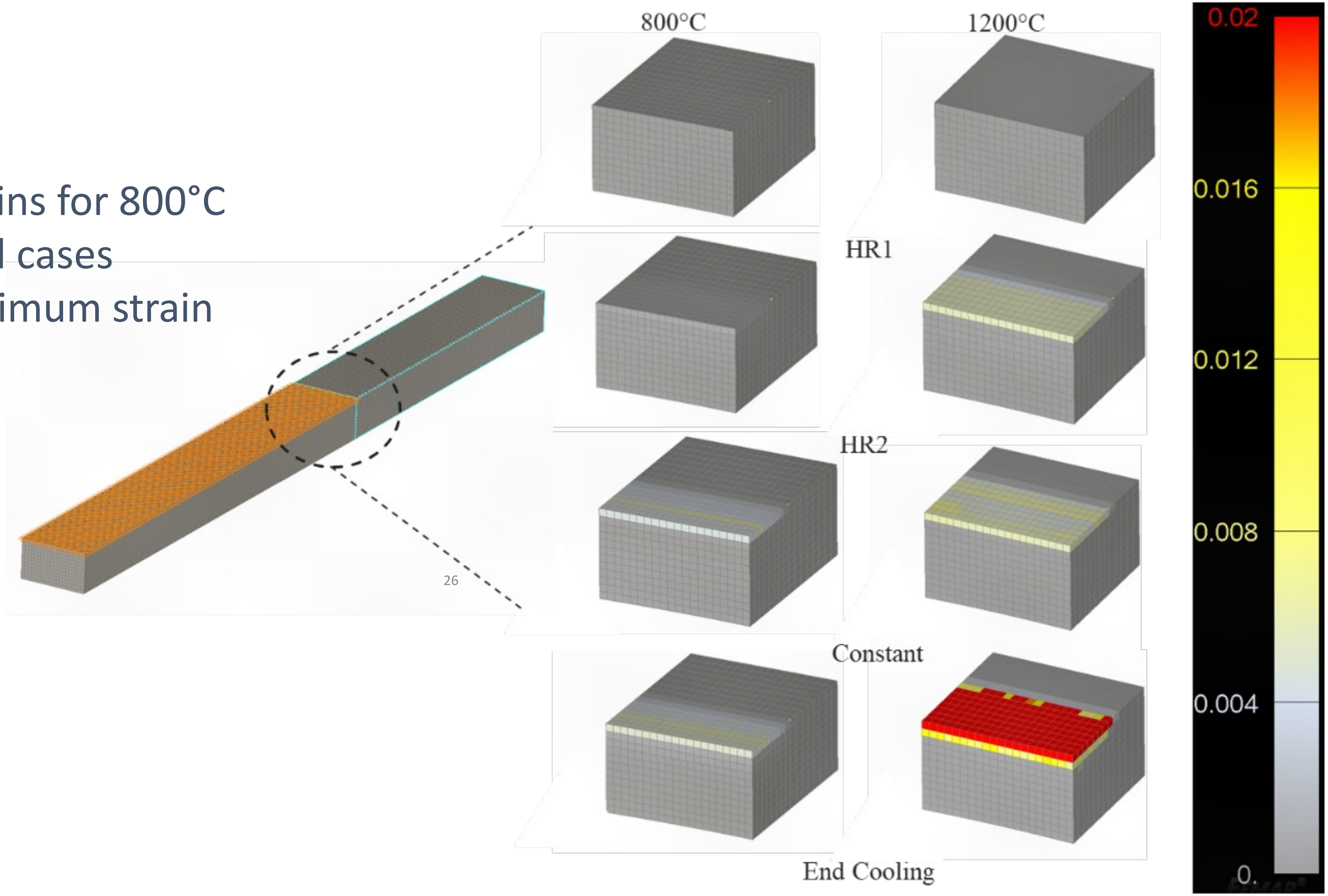
4. Thermal loads

Surface temperature boundary conditions implemented over time for launch condition (a) worst case, (b) more typical

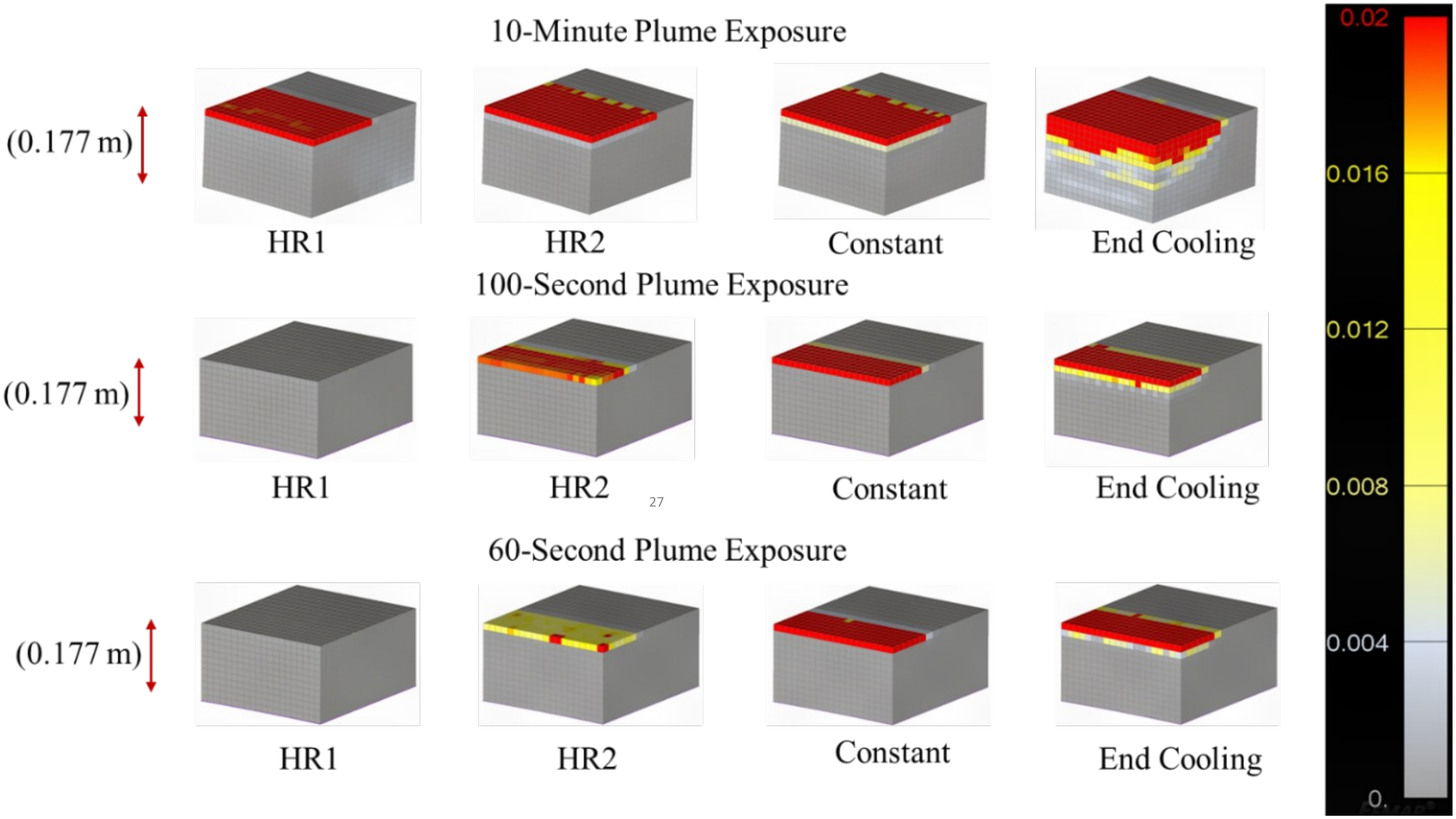


Analysis Results

Mechanical strains for 800°C and 1200°C load cases with a 0.02 maximum strain



Mechanical strains for 10 min, 100 sec and 60 sec plume exposure with a 0.02 maximum strain



Findings

- The initial value of LLP thickness must be at least 14 inches (~36 cm) for a 50-ton lander using assumed (ideal) properties of a microwave sintered material and is not influenced by the value of k.

- Cracking must be controlled through the use of an appropriate LLP thickness obtained using allowable tensile stresses, and results in the design thickness being insensitive to the value of k.

- Scientific data gathered on the above issues will be critical to inform the construction of structures that will sustain more than one landing/launch.

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Data We Need to Design Any Structure

- **LLP material properties must be obtained from standardized tests, at scale, to design.**
- **In situ, site-specific geotechnical properties including: regolith depth, specific gravity, void ratio, strength and stiffness depth profile, internal friction angle, etc.**

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- **For long-term durability, multiple performance factors will need to be considered: temperatures, hard vacuum, radiation, meteoroid impacts, seismicity, and pressure and temperature conditions during takeoff and landing.**
- **Simulants are not real regolith, and the variability of real regolith will need to be established.**

Closing Comments

- **Civil engineering certainly has the expertise and ability to safely build structures that perform under the most extreme conditions given the availability of data and standards to ensure that material performs repeatably and reliably.**

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- Recommendation: Build-observe-test-learn approach for the first LLP, preceded by acquiring the highest priority data from testing done in situ.

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- Civil engineering certainly has the expertise and ability to safely build structures that perform under the most extreme conditions given the availability of data and standards to ensure that material performs repeatably and reliably.
- Recommendation: Build-observe-test-learn approach for the first LLP, preceded by acquiring the highest priority data from testing done in situ.
- Without the necessary data, any structural design will need to be extra-conservative, and likely, expensive or potentially delayed due to technical knowledge gaps.

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- Recommendation: Build-observe-test-learn approach for the first LLP, preceded by acquiring the highest priority data from testing done in situ.
- Without the necessary data, any structural design will need to be extra-conservative, and likely, expensive or potentially delayed due to technical knowledge gaps.
- In situ measurements are necessary before one should make large investments or commitments to a particular location.
- Lunar science activities should prioritize this data to help realize safer and more reliable structures.

Acknowledgements

Website:
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PURDUE UNIVERSITY Discovery Park

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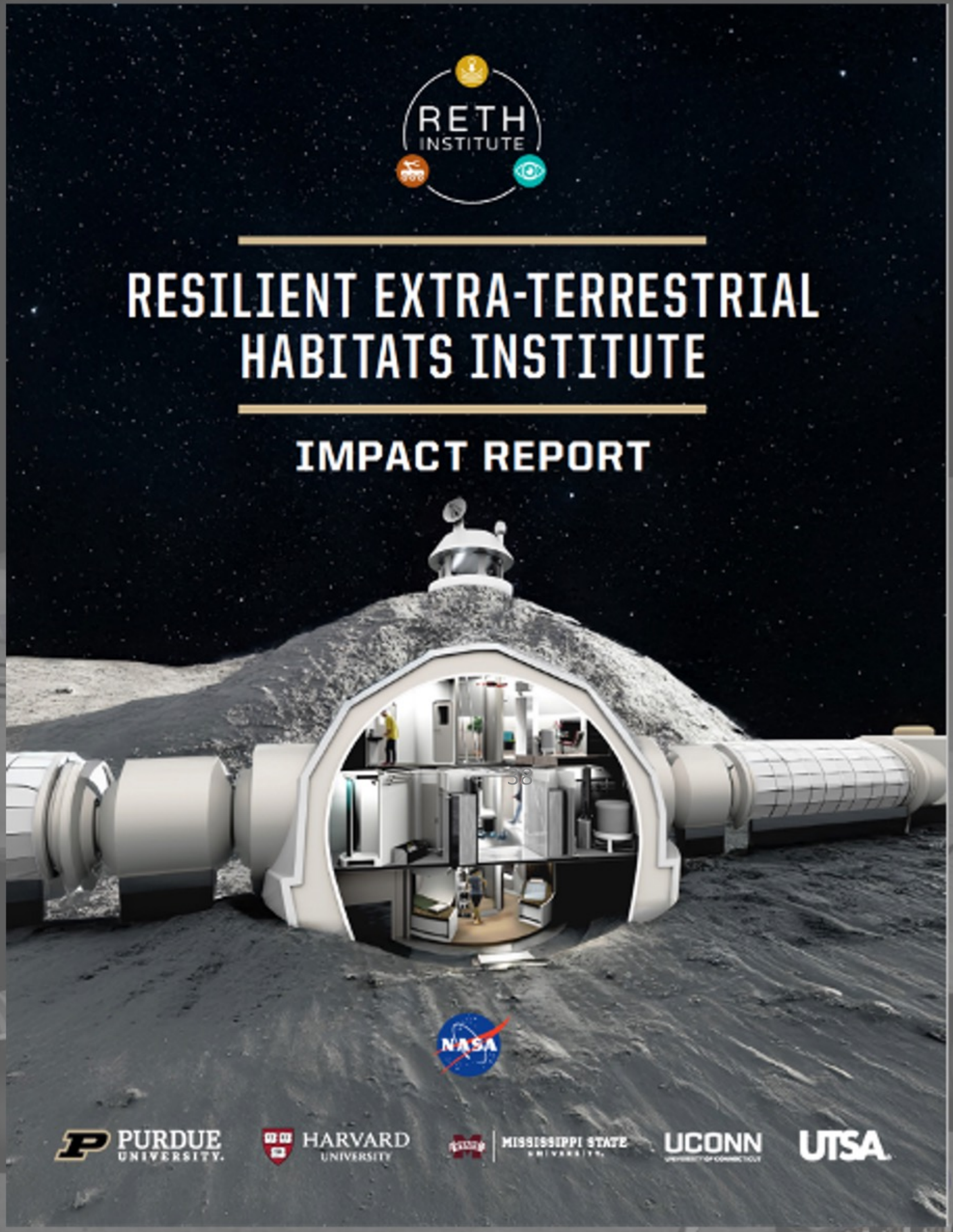

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This material is based upon work supported by NASA under award number 80NSSC19K1076.

Thanks to Dr. Takaharu Igarashi who generated the images of the RETH institute notional space habitat.