RESILIENCE FOR PERMANENT EXTRATERRESTRIAL HABITATS. A. Maghareh[1*], D. Gomez[1], S. J. Dyke[1,2], A. Bobet[1], J. Ramirez[1], H. J. Melosh[3], A. Modiriasari[1], and A. Theinat[1], [1,*]Lyles School of Civil Eng., Purdue University, W. Lafayette, IN 47907, amaghare@purdue.edu; [2]School of Mechanical Eng., Purdue University, W. Lafayette, IN 47907; [3]Dept. of Earth, Atmospheric, and Planetary Sciences, Purdue University, W. Lafayette, IN 47907.

Introduction: The evolution of space exploration will eventually lead to permanent extraterrestrial habitation. In 2015, NASA released its plan for establishing permanent settlements on Mars stating "We seek the capacity for people to work, learn, operate, and sustainably live beyond Earth for extended periods of time … Efforts made today and in the next decade will lay the foundation for an Earth-independent, sustained presence in deep space. Living and working in space require accepting risk and the journey is worth the risk" [1]. In addition, there are other organizations for which extraterrestrial colonization is the explicit goal. For instance, Elon Musk - the founder and CEO at SpaceX - has stressed many times that his goal is to make humanity a multiplanet species. It is within this context of establishing an *Earth-independent permanent extraterrestrial habitat* (EIPEH) system that we direct this study. The habitat system is intended to provide a living condition for more than 1,000 inhabitants, and will be designed to operate for at least 100 years.

In the context of permanent extraterrestrial habitation, resilience and safety should be given consideration early on. An EIPEH system should function, as intended, under continuous disruptive conditions, such as wild temperature fluctuations, galactic cosmic rays, as well as discrete disruptive events, such as meteoroid impacts, vibrations, solar particle events, and equipment failures. In this study, *resilience* is understood as the ability of a system to adapt, absorb and recover quickly from a disruption, whether expected or unexpected, without fundamental changes in function or sacrifices in safety. Note that resilience is an umbrella under which other factors can be found, for instance *reconfigurability*, *robustness*, *scalability* and *rapidity*. Reconfigurability is the ability to change configuration to enable an EIPEH system to perform at multiple system performance levels. Robustness is the ability of an EIPEH system to continue to function as intended during disruptive conditions. Scalability is the ability to grow, with resilience, the size of an EIPEH system. Finally, rapidity is the ability of an EIPEH system to repair structures and restore functionality in a timely manner, containing losses and avoiding cascading and/or escalating events.

In the current design of space structures/missions, *Failure Mode and Effect Analysis* (FMEA) and *Failure Modes, Effects and Criticality Analysis* (FMECA) are widely applied. FMEA and FMECA both allow identifying the product or process failure modes, estimating the risk associated with specific causes and prioritizing mitigating actions. Since the Challenger accident in the 1986, the optimistic perceptions about risk analysis changed and motivated NASA moving towards a more sophisticated risk management approach, *Probability Risk Assessment* (PRA), for major space missions, such as the International Space Station (ISS) [2]. Using PRA, the probability of a major accident can be obtained as a function of the probabilities of component and subsystem failures. The ISS PRA tool is an accident-scenario-based model of the Station that includes nearly 2,000 basic events, 400 sequences fed by nearly 450 fault trees resulting in 53 adverse end states [3]. However, from a system resiliency standpoint, the ISS has areas where a single failure could cause the loss of a major subsystem [3]. Indeed, in the context of an EIPEH system, a more comprehensive approach is needed which considers not only the identification of potentially major conditions/accidents and their causes but also the reaction, response, recovery, and performance level of the system subjected to disruptive and degrading conditions.

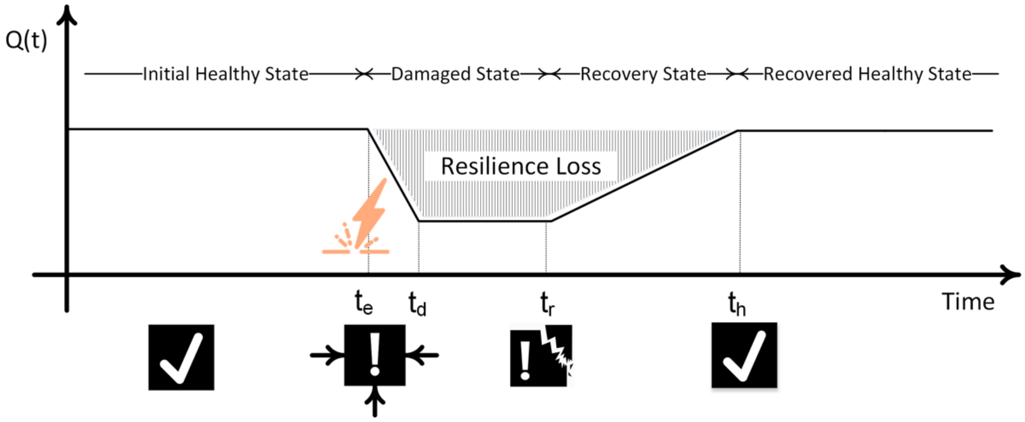

Figure 1. EIPEH state transition and its global resilience measure.

Approach: In civil engineering, the community has learned from past natural disasters and the impacts of failures driven by interdependencies among infrastructure sectors. Hurricane Katrina and the Fukushima nuclear disaster have revealed deficiencies in the design and analysis of such systems. As a result, the design methodologies for terrestrial structures have evolved and matured, leading to present performance-based design (PBD) and consequence-based design (CBD).

To design a safe and resilient EIPEH system, we have been developing a resilience framework based on the essential elements of these two design approaches. This framework provides a rationale for designing extraterrestrial structures under disruptive and degrading conditions considering their performance levels and operational dependencies. From a resilience standpoint, this framework addresses the five questions corresponding to an EIPEH system design subjected to disruptive and degrading conditions. What can go wrong? What is the likelihood? What is the recovery time? What are the consequences? What should be the level of preparedness? System resilience is, therefore, evaluated using a global resilience measure, Q(t) in Figure 1 which incorporates the answers to these questions. Next, PBD is employed as a means to ascertain or modify the likely performance of structures to achieve minimum loss.

In civil engineering, PBD came into existence as a means to ascertain the likely performance of structural and infrastructure systems subjected to natural hazards. A PBD matrix maps different hazard levels to performance levels, see Figure 2, thus, structures are designed to perform in different structural performance levels (PL-I … PL-IV) based on the consequences of their failure on the resilience of an EIPEH system. For each structure at each performance level, an estimation of life loss, functionality loss, and recovery time are attributed.

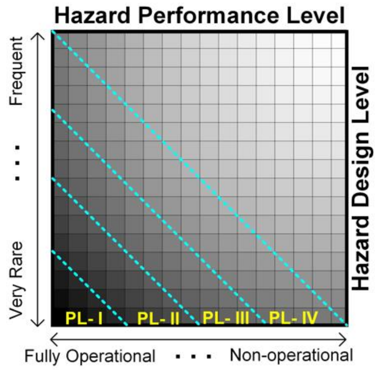

Figure 2. Performance based design matrix.

In this framework, an EIPEH system is modeled as a *complex interconnected system*. Complex interconnected systems are characterized by a high degree of technical complexity, social intricacy, and elaborate processes [4]. In a complex interconnected system, there are four categories of interdependencies, *physical interdependency* (i.e., physical coupling between inputs and outputs of subsystems), *cyber interdependency* (i.e., the state of subsystems depends on the information transmitted), *geographical interdependency* (i.e., one or several subsystems are in close proximity so that one event creates disturbances to the entire system) and *logical interdependency* (i.e., a subsystem is logically dependent if its state of operations depends on the state of other subsystems via a mechanism that is not a physical, cyber, or geographic connection) [5]. For an EIPEH system, a key to achieving its intended purpose is that its critical structures function properly and provide/generate essential services, such as thermal control, power, life-support, pressure control, in-situ resources, command, control and communication, etc. These structures do not operate in isolation but interdependently.

In addition, interdependencies between structures are modeled based on *Systems Operational Dependency Analysis* [6]. Each dependency is represented with three parameters: *strength of dependency* (SOD), *criticality of dependency* (COD), and *impact of dependency* [6], see Figure 3. SOD accounts for how much the functionality of the structure (k) depends on the functionality of the structure (i or j). COD and IOD quantify how the functionality of the structure (k) degrades when the structure (i or j) is experiencing a failure. Here, dependencies are modeled as piecewise linear relationship, suitable to analyze various scenarios, including partial dependencies.

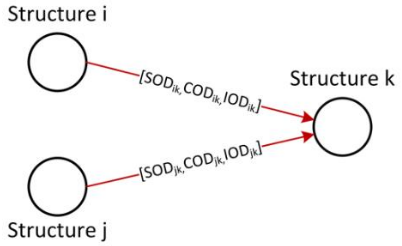

Figure 3. Synthetic model of feeder-receiver structures.

Summary: This abstract provides an overview of a resilience framework, developed in the Resilient Extra-Terrestrial Habits at Purdue University [7], to design a safe and resilient EIPEH. Here, some desired properties of EIPEH systems are considered, such as reconfigurability, robustness, scalability and rapidity. Moreover, this framework adopts the essential elements of two civil engineering design approaches, PBD and CBD.

References: [1] NASA (2015) *NASA's Journey to MARS.* [2] Patriarca R. et al. (2016) *8th IAASS*, 228-239. [3] International Space Station Independent Safety Task Force (2007) *Final Report of the International Space Station Independent Safety Task Force.* [4] de Weck O. L. et al. (2016) *Engineering Systems: Meeting Human Needs in a Complex Technological World*. [5] Hokstad P. and Utne I. B. (2012) *Risk and Interdependencies in Critical Infrastructures.* [6] Guariniello C. and DeLaurentis D. (2017) *Research in Engineering Design*, 28, 53-69. [7] Dyke S. J. et al. (2018) *49th LPSC,* Abstract.