Complex Networks Perspectives towards Accelerated Bridge Construction (ABC)

Quarterly Progress Report
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1. Background and Introduction

Accelerated Bridge Construction (ABC) employs precast bridge elements moved to the bridge location and installed in place. Although ABC advances the life cycle cost (while using new materials and methods), reduce construction time, and result in higher quality of elements, nevertheless many cast-in-place activities need to be undertaken. As such, despite the fact that ABC reduces many uncertainties associated with construction processes and performance during service life, ABC related activities can create impacts on the road network carrying regular traffic. The problem may get escalated during major natural extreme events (hurricane, wildfire). As such, network positions or credentials of bridges based on their topography or connectivity need to be assessed to prioritize or stage ABC activities. There have been limited investigations by many states to monitor the effects on traffic due to ABC related activities and to identify more efficient strategies to pursue such activities while reducing overall system-wide impact. ABC-UTC is planning to embark on a coordinated and extensive network experiments at different geographic scales to apply complex network science principles to the study of bridge networks and ABC related activities. The research will use GIS modeling along with FDOT bridge and road network data to run network experiments and prioritize certain bridges based on their network credentials. Essentially, it will be attempted to establish relationships between bridge topography with their functional behavior. The research will provide new insights into ABC activities and scheduling based on the topography of vulnerable bridges and monitoring system-wide cascading effects. The results will be compiled and published on ABC-UTC website and will become available to outside users and researchers. The study will develop an approach and tool that states, municipalities and other transportation authorities can use to select the proper actions for repair and replacement of exiting bridges by implementing ABC methods of choice and on a risk-based maintenance strategy.

2. Problem Statement

Conceptual and methodological developments in network analysis have furthered our understanding of the effects of individuals' interpersonal environment on normative social influence and social engagement. Network data offers better insights related to an individual's abilities, aspirations, attitudes, behaviors, and interpersonal environment. The complex topology of real networks allows its actors to change their functional behavior. Network models provide better understanding of the evolutionary mechanisms being accountable for the growth of such networks by capturing the dynamics in the ways network agents interact and change their behavior. Considerable amount of research efforts is required for developing novel network modeling techniques to understand the structural properties such networks, reproducing similar properties based on empirical evidence, and designing such networks efficiently.

ABC project applications are categorized in 6 tiers based on the project mobility/traffic impact time ranging from 1 day (Tier 1) to several months (Tier 6), with considerable reduction of time from the conventional option. For example, a project for which the entire superstructure has been assembled off-line and moved in place within just 24 hours will be specified as Tier 1 (Shane 2018). Tier 6 will include impacting for example a statewide bridge replacement program by months or years through implementing Tier 1 to 5 projects for individual bridges in the network. However, these options may translate to variable costs normally higher costs for shorter duration. Consequently, selection of the ABC method will impact the cost according to the advantage it offers for time. This trend is one of the factors to be considered on the network analysis for ABC options along with others.

Identifying the vulnerable sections and cascading effects in the bridge network system can be quite challenging. Potential failure in a bridge network system is often over-looked, but the consequence can be catastrophic as it can adversely affect the mobility of people. Therefore, addressing the vulnerabilities is very complicated in large cities. While there have been studies that discussed the necessity of developing framework for measuring resilience, a systematic approach to improving resiliency through vulnerability assessment is lacking. The objective of this study is to present method for assessing the vulnerability of a bridge network system and a strategy for improving its resiliency. With a growing attention to risk-based inspection and maintenance of infrastructure, an accurate knowledge of the vulnerabilities and importance, as well as consideration of interrelation among bridges in a network becomes crucial. The bridge network system in the state of Florida, USA will be used as a case study in this project.

The vulnerability and resilience of the Florida bridge network will be analyzed based on network science principles and graph theory. For example, the bridge connectivity will be treated as a network to assess the interdependence between the connectivity of the system components and their functional behavior (Newman 2003). In accordance with the network science literature, these network links and nodes can be analyzed with respect to the resilience metrics to determine the critical components of a bridge network system that are more susceptible to external shocks. Once the vulnerabilities have been identified, priorities will be set to improve the different vulnerable sections of the bridge network system. Furthermore, a plan will be developed, to improve the resiliency of all the different components of the bridge network systems. A preliminary literature review is provided in section 4.2 to motivate how network science principles can be applied to the study of bridge networks and Accelerated Bridge Construction (ABC) activities.

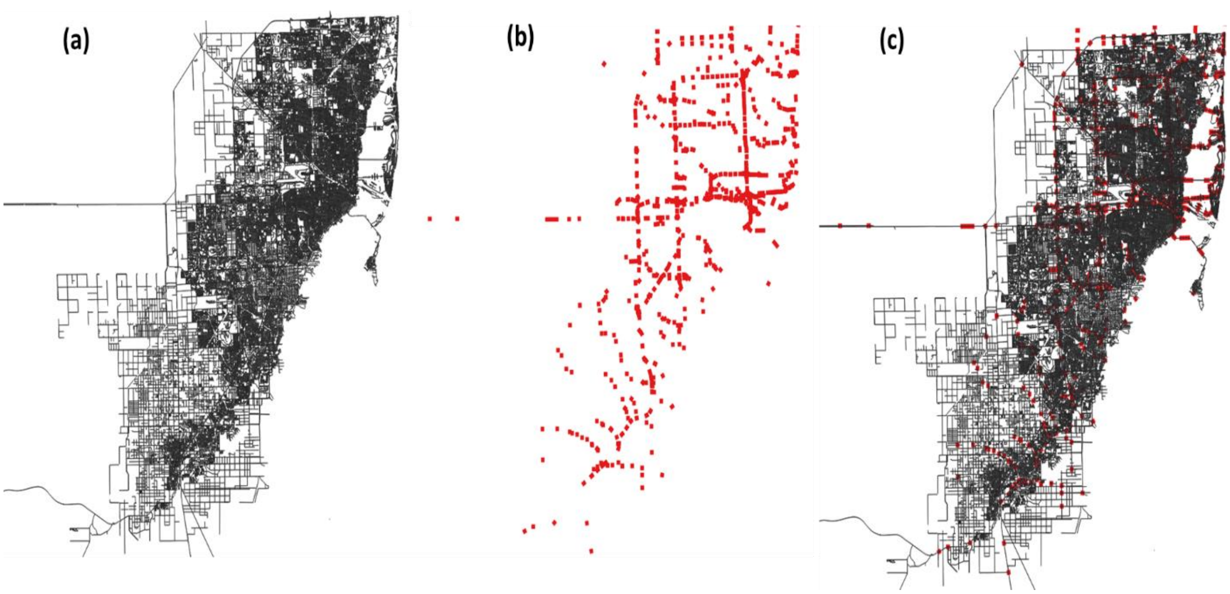

FIGURE 1: Examples of Miami-Dade and Broward county road and bridge network. (a) Road network, (b) Bridge network, (c) Superimposed road and bridge network.

3. Objectives and Research Approach

ABC-UTC is planning to embark on a coordinated and extensive network experiments at different geographic scales to apply complex network science principles to the study of bridge networks and ABC related activities. The research will use GIS modeling along with FDOT bridge and road network data to run network experiments and prioritize certain bridges based on their network credentials. Essentially, it will be attempted to establish relationships between bridge topography with their functional behavior. The specific objectives of the proposed project include *(a) investigation on the resiliency and vulnerability of road-bridge networked systems, (b) development of a framework for analysis of such networks and their topology with functional behavior, (c) incorporation of the analysis method in a user friendly tool for use by bridge owners and consultants for decision making on maintenance of the infrastructure, and (d) incorporation of complex network analysis with ABC options and features*

The research will provide new insights into ABC activities and scheduling based on the topography of vulnerable bridges and monitoring system-wide cascading effects. By applying network science principles, most important (higher degree and more central) bridges among the bridge network will be identified. We can then suggest ABC to put more emphasize (maintenance, retrofitting) on those bridges; which can facilitate recovery of bridge networks after an extreme event, hence ensuring resiliency. Similar context can be applied to new ABC activities. The results will be compiled and published on ABC-UTC website and will become available to outside users and researchers. The study will develop an approach and tool that states, municipalities and other transportation authorities can use to select the proper actions for repair and replacement of exiting bridges by implementing ABC methods of choice and on a risk-based maintenance strategy.

4. Description of Research Project Tasks

The following is a description of tasks carried out to date.

Task 1 – Comprehensive Literature Review

A comprehensive literature review has been completed in this quarter which is detailed below:

Transportation infrastructure forms the mainstay of the economy and typically requires huge amount of annual investments which are mainly for maintenance, rehabilitation, and replacement of the assets of the transportation infrastructure. The overall expenditures are expected to increase due to infrastructure aging, increased frequency and intensity of severe weather, and increasing traffic loads. More than 685,000 bridges in the United States are no exception to these conditions. The vitality of the bridge network to the transportation network and to economic development, the large investments in their repair and replacement, and the impact of their closures on the socio-economic prosperity of the society, inspires the implementation of new construction techniques, planning approaches, and policies for their management. One of the main challenges facing transportation asset managers is the need to cost-effectively prioritize the repair and replacement of the large inventory of deteriorating bridges considering the ever-increasing budgetary constraints. The indirect costs (such as traffic delay) associated with the closure times during these activities exacerbates the decision-making processes (Alice Alipour 2018).

As an alternative to conventional construction, Accelerated Bridge Construction (ABC) techniques are gradually gaining acceptance to reduce construction duration and minimize the impact of closures at the network level. There are different types of ABC and each technique has its limitations and speed of completion. The choice of using a specific ABC depends on a host of different factors including its applicability to specific bridge site, criticality of the bridge to the network, and availability of capital funds for its implementation. Some of these factors tend to have contradicting affects, as a faster ABC technique often entails higher investment levels; on the other hand, a faster technique for a bridge with high criticality to the network may result in large savings in user costs (Alice Alipour 2018).

Alice et al. aims to address the aspects through a review of the available literature and having interview with a few states that have implemented ABC at different levels. The results showed that the major aspects impacting the timelines for ABC projects are the impacts the closures might have on the socio- economic aspects of the community. Hence, most states acknowledge the importance of indirect costs, except for some, there is no mathematical formulation to account for them in the final decision making. Most of decisions are made based on the qualitative input from districts and through public discussions with the public. For the establishment of incentives, similar procedure as those for the conventional construction and following the FHWA guidelines is suggested by most of the states (Shane 2018).

To support resilience planning for roadway networks, Zhang et al. introduces a new stage-wise decision framework regarding pre-disaster mitigation (Stage I), post-disaster emergency response (Stage II) and long-term recovery (Stage III). These decision metrics are first defined, based on a derivation of the number of independent pathways (IPW) within a roadway system, to measure the performance of a network in term of its robustness, redundancy, and recoverability, respectively. In Phase I, a prioritization approach for temporary repairs to facilitate immediate post-disaster emergency responses in Phase II, and a methodology for scheduling network-wide repairs during the long-term recovery of the roadway system in Phase III. Using the three IPW-based decision metrics, a stage-wise decision process is then formulated as a stochastic multi-objective optimization problem, which includes a project ranking mechanism to identify pre-disaster network retrofit projects. Finally, this stage-wise decision framework is applied to the roadway network of Shelby County, TN, USA subjected to seismic hazards, to illustrate its implementation in supporting community network resilience planning (Zhang 2018).

Machado et al explains community resilience which depends on the resilience of the lifeline infrastructure and the performance of the disaster-related functions of local governments. This study summarizes the metrics used to assess the resilience of the transportation system and a categorization of the assessment approaches at three levels of analysis (the asset, network, and systems levels). State and federal resilience plans and guidelines acknowledge the importance of the transportation system as a critical lifeline in planning for community resilience and in helping local governments to set recovery goals. However, a widely accepted definition of the resilience of the transportation system and a structure for its measurement are not available. Furthermore, this paper ties these metrics to relevant dimensions of community resilience. This work addresses a key first step required to enhance the efficiency of planning related to transportation system resilience by providing (a) a standard terminology with which efforts to enhance the resilience of the transportation system can be developed, (b) an approach to organize planning and research efforts related to the resilience of the transportation system, and (c) identification of the gaps in measurement of the performance of the resilience of the transportation system (Machado-León 2017).

Sun et al states that the transportation infrastructure plays an important role in ensuring the well-being of its citizenry and for supporting the national economy. There is an increasing number of studies focusing on the resilience analysis of the transportation infrastructure to support planning and design and to optimize emergency management and restoration schedules. Extreme events (including both natural hazards and man-made disasters) have caused terrible physical damages to the transportation infrastructure, long-term socioeconomic impacts, and psychological damages. This study covers functionality metrics, functionality-based resilience metrics and socio-economic resilience metrics. The study also revealed that there are still fundamental challenges to comprehensively evaluate the resilience of the transportation infrastructure, especially due to two main sources of complexity: uncertainties and interdependencies. Besides, the validations of resilience assessments are limited due to the general scarcity of data, which may hinder the practical applications (Sun 2018).

4.1 Resiliency of Bridge Network

Alice et al develops a mixed-integer programming model that provides a balanced portfolio of construction techniques on bridge sites over a prioritization process for bridges at the network level. A project-level scheme accordingly is conducted to optimize the choice of accelerated construction techniques for this purpose, while a network-level scheme is used to select the bridges for rapid replacement based on their criticalities to the network, To account for the effects of different accelerated construction techniques, the costs associated with each replacement technique is calculated including direct costs from the actual replacement of bridges and indirect costs experienced by network users due to the bridge closure during the maintenance period (Alice Alipour 2018).

Twumasi et al. explains hazard impacts on regional network infrastructures and identifying significantly affected areas are important for communicating the need for building resilient infrastructure by describing the comprehension of network-level consequences resulting from disruptive events is a main gray area in the evaluation of transportation network resilience at the regional level. High-impact-zone location identification metrics were developed and implemented in preliminarily identifying areas affected by bridge closures. This study presents a framework for assessing the regional network resilience by leveraging scenario-based traffic modeling and GIS techniques Resilience was estimated, and an index developed by utilizing practical functionality metrics based on vehicle distance and hours traveled. These are illustrated for the Tampa Bay, Florida, area. Findings for 10 bridge closure scenarios and recovery schemas indicated significant regional resilience losses. The I-275 bridge closure indicated the highest functional loss to the regional network: the aggregated resilience index below 0.5 reflects severe network performance deficit and mobility limitations (Twumasi-Boakye 2018).

Zhang et al. presents a methodology systematically incorporates network topology, redundancy, traffic flow, damage level and available resources into the stochastic processes of network post-hazard recovery strategy optimization. A novel resilience-based framework is developed here to optimize the scheduling of the post-disaster recovery actions for road-bridge transportation networks. Two metrics are proposed for measuring rapidity and efficiency of the network recovery: total recovery time (TRT) and the skew of the recovery trajectory (SRT). The TRT is the time required for the network to be restored to its pre-hazard functionality level, while the SRT is a metric defined for the first time in this study to capture the characteristics of the recovery trajectory that relates to the efficiency of those restoration strategies considered. To illustrate the proposed methodology, a genetic algorithm is used to solve the restoration schedule optimization problem for a hypothetical bridge network with 30 nodes and 37 bridges subjected to a scenario seismic event. Based on the two-dimensional metric, a restoration scheduling method is proposed for optimal post-disaster recovery planning for bridge-road transportation networks. A sensitivity study using this network illustrates the impact of the resourcefulness of a community and its time-dependent commitment of resources on the network recovery time and trajectory (Zhang 2017).

Frangopol et al. claims that the most earthquake damage prone components of a transportation network are certainly its bridges; therefore, the proposed approach focuses on bridge rehabilitation interventions. This study deals with the concept of "resilience" and proposes its use as optimization criterion for the rehabilitation of a transportation network subject to earthquake. The design variables of the optimization problem are the application times and durations of the interventions on bridges of the network. These durations are determined by the amount of funding invested on each bridge. Hence, the proposed methodology provides the optimal rehabilitation schedule and cost breakdown for all the bridges of the network. A numerical application is presented to illustrate the proposed approach and to show its capabilities (Frangopol 2011).

Bocchini et al. describes that the development of tools for the assisted decision making during the disaster management is the most promising fields where the concept of resilience is applied to engineering practice. The proposed technique involves a completely new formulation of the optimization problem, with new design variables, additional objectives, and constraints. This new technique for the optimal disaster management is presented here that provides bridge restoration sequences which maximize the network resilience and minimize the time to connect critical locations. The purpose of these modifications is to generate an automated procedure that mimics better the decision process currently used by disaster managers. Two numerical examples are presented: the first one is meant to validate and demonstrate the proposed approach, whereas the second proves its applicability to a network with a larger number of bridges. In this latter example the input data have been filtered by random factors to make the data more realistic (Bocchini 2013).

Karamlou et al. indicates transportation networks as necessary infrastructure elements to provide supports to impacted areas after the occurrence of a disaster. Recovering without functional roads, other damaged facilities and lifelines would be slow and difficult. Therefore, restoring the damages of transportation networks, specifically bridges as their most vulnerable elements, is among the first priorities of disaster management officials. This study develops a new methodology for the restoration of damaged bridges scheduling by developing an algorithm which is providing a practical restoration plan to be used by decision makers at the time of an event, yet based on solid computations rather than mere engineering judgment. The problem is formulated as a multi-objective combinatorial optimization solved by Genetic Algorithms, which minimizes the time to connect the selected critical locations and maximizes the resilience of the transportation network. The algorithm is examined with a numerical example. The presented algorithm can be considered as the enhancement of previous work performed at Lehigh University. The results show that the

new optimization setup improved the solution quality and efficiency compared to the previous techniques (Karamlou 2014).
Banerjee et al. provided an organized and wide-ranging review on bridge and bridge network resilience assessment under single hazard and multi-hazard conditions. Resilience assessment for engineered systems in recent years has attracted considerable attention from the engineering community. It has resulted in a large body of literature that focuses on relevant areas of resilience. Authors mentioned not that much work has yet been done on multi-hazard bridge resilience, relevant aspects are discussed, including combinations of multiple hazards for bridge performance assessment, loss assessment methods, and post-event recovery approaches. In addition, maintenance is a key component when a life-cycle framework evaluates resilience. Accessible maintenance plans and strategies are discussed as well as their likely applications for bridges and bridge networks. The article ends with a debate on the need for more work in the focus area and the challenges associated with it (Banerjee 2019).

Domaneschi et al. stated that structural management systems can make a significant contribution to reducing the impact of extreme events in areas affected by the earthquake, thus improving structural resilience. In addition, as structural conditions change due to local failures, the inherent advantage of some control systems, which can adjust to various loading rates, can be exploited. This happens by changing the control system's working parameters in real time or over the period between two seismic events, even if very short. This research deals with the durability of cable-stayed bridge seismic control solutions through a case study defined by a standard literature bridge control benchmark. Authors introduced a technique to restore the optimum bridge configuration after a damaging incident. Emphasis is placed on the time interval between the occurrence of damage and the recovery, which is the essential aspect of the resilient actions. Ultimately, in the sense of multiple hazards, the development of a robustness index and general procedures indicating how to measure durability for the cable-stayed bridge control system is discussed (Domaneschi 2015).

Bocchini et al. discussed an optimization method for the reconstruction activities associated with the bridges of an earthquake-seriously damaged transportation network. The development variables are (i) the time periods between the occurrence of the distress and the start of the interventions on each network bridge; and (ii) the rate of reconstruction of the interventions, which is a measure of the funding allocated to each bridge. The optimization goals were to optimize the efficiency of the network, reduce the time required to reach a target level of functionality, and minimize the total cost of restoration activities. Since the first two goals obviously clash with the last, the optimization approach does not provide a unique solution, but a whole array of Pareto solutions. The capabilities of the proposed methodology are illustrated by a numerical example involving a complex, existing transport network in Santa Barbara, California (Frangopol 2012).

Apostolopoulou et al. explained that sustainable monument conservation requires the use of performing materials that are at the same time compatible with the historical building materials of the monument to ensure structural integrity, sufficient structural quality in earthquake strain, and stability of both reconstruction and historical materials. It refers in particular to cultural heritage properties that have suffered major damage, requiring extensive restoration. After a heavy rainfall in 2015, the Plaka Bridge in Epirus, Greece, partly collapsed. It was a supreme example and an important symbol of the region's typical stone bridge architecture. In this study, through a variety of laboratory techniques, a potential restoration stone from a nearby quarry was examined in terms of compatibility with the bridge's dominant historical building stone, as well as in terms of mechanical performance. Furthermore, criteria for the restoration of mortars were set, taking into account the characteristics of the historical materials as well as the bridge environment. The results of the study on restoration stone and mortars were presented and evaluated to select the most suitable restoration materials for Plaka Bridge in its upcoming reconstruction, with the goal of improving the structure's overall resilience (Apostolopoulou 2019).

Setunge et al. stated that the road networks and critical road systems such as bridges, culverts and floodways play a vital role in increasing the risk of the area being served before, during and after extreme events. The research presented a detailed analysis of the Lockyer Valley region of Australia's case study of 2013 floods to identify critical failure mechanisms of road bridge structures exposed to flood events. 43 out of 46 bridges in the region have been damaged as a result of the 2013 flood. Major bridge structure failure mechanisms are described as scouring of piers and abutments, damage to bridge decks due to impact of urban debris, and severe damage to bridge approach ramps. A methodology is proposed for vulnerability modeling of bridges for an extreme event, consisting of a combination of the definition of fault tree system and harm index (Setunge 2014).

Karamlou et al. presented a new scheduling methodology to restore damaged bridges. The problem is formulated as a multi-objective combinatorial optimization solved by Genetic Algorithms which minimizes the time to connect the critical locations selected and maximizes the transport network's resilience. The main purpose of designing the algorithm was to provide a restore strategy that is realistic to be used at the time of an incident by decision-makers, but based on solid computations rather than pure judgment of technology. A statistical example explores the algorithm. The results show that, compared to previous approaches, the current optimization system improved the quality and efficiency of the solution (Karamlou 2014).

Zhang et al. proposed a new resilience-based framework for street-bridge transport networks to optimize the scheduling of post-disaster recovery actions. Systematically, the approach integrates network topology, reliability, traffic flow, damage level and available resources into the design of the post-hazard recovery strategy network stochastic processes. Two metrics were proposed to calculate network recovery speed and efficiency: total recovery time (TRT) and the skew of the recovery trajectory (SRT). The TRT is the time required to restore the network to its pre-hazard level of functionality, while the SRT is a metric established for the first time in this study to capture the characteristics of the recovery path that are linked to the efficiency of those strategies considered for restoration. A sensitivity study using this network illustrates the impact on the network recovery time and trajectory of a community's resourcefulness and its time-dependent resource commitment. A restore scheduling method for optimal post-disaster recovery planning for bridge-road transport networks is proposed based on this two-dimensional metric. A genetic algorithm is used to solve the problem of restore schedule optimization for a hypothetical bridge network with 30 nodes and 37 bridges subjected to a seismic scenario case to explain the suggested technique (Weili Zhang 2017).

Tao et al. described that bridge quality can deteriorate due to aging, traffic-induced fatigue, and environmental corrosion throughout their lifetime. Structural instability in earthquake-prone areas raises bridge seismic vulnerability, which means an increase in potential future economic and social losses. Therefore, determining the optimum maintenance strategies with regard to bridge deterioration is of critical importance. To this end, the present paper proposes an infinite-horizon hybrid Markov decision process model in which both the occurrence of earthquake and structural deterioration processes are integrated into a unified Markovian framework. A Markov chain is modeled on the structural deterioration process and a simplified earthquake-induced probability transition matrix is adopted. The proposed model is applied to a simple case study for demonstration purposes (Tao 2019).

Pritchard (2013) identified a range of issues that have been encountered as a result of the floods and cyclone events from 2011 to 2012 in Queensland, Australia. These included timber bridge destruction, pier settlement, abutment scouring, and the loss of road approaches to bridges. The AS 5100 Bridge Design Code is assumed to have been written primarily for traditional rural applications. In addition, this paper discusses the specific loads to which urban bridges are subject, including floating debris such as shipping containers, vehicles and river-craft (e.g. 300 t vessels) to be included in future revisions of AS 5100. Bridge design codes were suggested to consider the context and location of bridges for accessibility and usability after catastrophe in the future. It is recommended that such training be considered and implemented in accordance with suggested changes to the AS 5100 Bridge Design Code for new bridges and remedial works (Pritchard 2013).

All the reviewed papers are associated with the resiliency of bridge network, which are providing meaningful insights for both response and recovery phases of a disaster. Single hazard and multi-hazard resiliency assessment for highway bridge network highlighted the importance of bridge maintenance work. For cable stayed bridges, a robustness index and general procedures are developed to measure durability during an earthquake event. Markovian framework is proposed for optimum maintenance of deteriorating bridges and a multi-criteria intervention optimization process is formulated for restoration of bridge networks in earthquake-prone areas. Besides, an evaluation of new building materials for its restoration is discussed for the Plaka bridge in Epirus. A framework for vulnerability bridge modeling for an extreme flood is proposed, consisting of a combination of the defect tree structure description and the harm list. As consequences for flood and cyclone events; timber bridge destruction, pier settlement, abutment scouring, and the loss of road approaches to bridges are identified. Then, a new scheduling methodology is introduced to restore damaged bridges to optimize bridge restoration sequence for resilient transportation networks. Two metrics are proposed to calculate network recovery speed and efficiency: total recovery time (TRT) and the skew of the recovery trajectory (SRT). These important metrics can influence the criterions for planning, evaluation and rebuilding guidelines of bridge network.

4.2 Review of Network Science Literature

Many new network concepts, properties and measures have been developed by running experiments on large-scale real networks. A number of statistical properties and unifying principles of real networks have been identified from these studies. Significant amount of research efforts have helped to develop new network modeling tools, reproduce the structural properties observed from empirical network data, and design such networks efficiently with a view to obtaining more advanced knowledge of the evolutionary mechanisms of network growth (Hasan and Ukkusuri 2011). Many real networks possess interesting properties unlike random graphs indicative of possible mechanisms guiding network formation and ways to exploit network structure with specific objectives (Newman 2003). Some of these properties, common across many real networks, are described below:

4.2.1 Small-world Property

This property refers to the existence of relatively short paths between any pair of nodes in most networks despite their large size. The existence of this property is evident in many real networks (Milgram 1967, Travers and Milgram 1969, Watts and Strogatz 1998). The small-world effect has important implications in explaining dynamics of processes occurring on real networks. In case of spreading information or ideas through a network, the small-world property suggests that the propagation will be faster on most real world networks because of short average path lengths (Newman 2003). Three important measures to explain this property are eccentricity, radius and diameter. While the eccentricity of a node in a graph is the maximum distance (number of steps or hops) from that node to all other nodes; radius and diameter are the minimum and maximum eccentricity observed among all nodes, respectively.

4.2.2 Degree Distributions

The degree of a node (k) is the number of direct links to other nodes in a graph. The degree distribution $P(k)$ in real networks (probability that a randomly chosen node has degree k, issignificantly different from the Poisson distribution, typically assumed in the modeling of random graphs. In fact, real networks exhibit a power law (or scale-free) degree distribution characterized by higher densities of triangles (cliques in a social network, for example) (Barabási and Albert 1999). In addition, many real networks also exhibit significant correlations in terms of node degrees or attributes. This scale-free property validates the existence of hubs, or a few nodes that are highly connected to other nodes in the network. The presence of large hubs results in a degree distribution with long tail (highly right-skewed), indicating the presence of nodes with a much higher degree than most other nodes. For an undirected network, the degree distribution $P_{degree}(k)$ can be written as follows:

$$P_{degree}(k) \propto \ k^{-\gamma} \tag{1}$$

where γ is some exponent and $P_{degree}(k)$ decays slowly as the degree k increases, increasing the probability of obtaining a node with a very high degree. Networks with power-law distributions are called scale-free networks (Albert and Barabási 2002) that holds the same functional form (power laws) at all scales. The power law $P_{degree}(k)$ remains unchanged (other than a multiplicative factor) when rescaling the independent variable k by satisfying:

$$P_{degree}(xk) = \ x^{-\gamma} P_{degree}(k) \tag{2}$$

The presence of hubs that are orders of magnitude larger in degree than most other nodes is a characteristic of power law networks. In this study, we test the scale free property both for the activity frequency of all active nodes and the degree distribution of subgraphs being active at different activity levels.

4.2.3 Transitivity

This property is a distinctive deviation from the properties of random graphs. Network transitivity implies that two nodes are highly likely to be connected in a network, given each of the nodes are connected to some other node. This is indicative of heightened number of triangles that exist in real networks (sets of three nodes each of which is connected to each of the others) (Newman 2003). The existence of triangles can be quantified by *Clustering Coefficient. C:*

$$C = \frac{3 * Number\ of\ triangles\ in\ the\ network}{Number\ of\ connected\ triples\ of\ nodes} \quad (3)$$

A *connected triple* refers to a single node with links running to an unordered pair of others. In case of social networks, transitivity refers to the fact that the friend of one's friend is likely also to be the friend of that person. Another important notion is *Network Density*, frequently used in the sociological literature (Scott 2012). The density is 0 for a graph without any link between nodes and 1 for a completely connected graph.

4.2.4 Network Resilience

This property, related to degree distributions, refers to the resilience of networks as a result of removing random nodes in the network and the level of resilience to such vertex removal varies across networks depending on the network topology (Newman 2003). Networks in which most of the nodes have low degree have less disruption since these nodes lie on few paths between others; whereas removal of high degree nodes in a large real network can result in major disruption. The usual length of these paths will increase if nodes are removed from a network, resulting in disconnected pairs of nodes and making it more difficult for network agents to communicate.

4.2.5 Node-level Properties

Node Degree

The node degree is the number of edges adjacent to that node (deg_i). In-degree is the number of edges pointing in to the node (in_deg_i) and out-degree is the number of edges pointing out of the node (out_deg_i). Average neighbor degree refers average degree of the neighborhood ($z_{n,i}$) of each node i is:

$$z_{n,i} = \frac{1}{|N_i|} \sum_{j \in N_i} z_j \quad (4)$$

where, $N(i)$ are the neighbors of node i ; z_j is the degree of node j that belongs to N_i. In case of weighted graphs, weighted degree of each node can be used (Barrat, Barthelemy et al. 2004).

Clustering Coefficient

In case of an unweighted graph, the clustering coefficient (cc_i) of a node i refers to the fraction of possible triangles that exist through that node:

$$cc_i = \frac{2\,T_i}{deg_i * [deg_i - 1]} \quad (5)$$

where, T_i is the number of triangles that exist through node i and deg_i is the degree of node i. In case of weighted graphs, this clustering coefficient can be defined as the geometric average of the sub-graph edge weights (Saramäki, Kivelä et al. 2007). The eccentricity of node i is the maximum distance from node i to every other nodes in the graph G (ecc_i).

Betweenness Centrality

Out of a number centrality measures, betweenness centrality (BC_i) of node i is the sum of the fraction of all-pairs of shortest path that pass through node i:

$$BC_i = \sum_{x,y \in V} \frac{\theta_{(x,y \mid j)}}{\theta_{(x,y)}} \tag{6}$$

where, V is the set of nodes in G, $\theta_{(x,y)}$ is the number of shortest (x, y) paths, and $\theta_{(x,y \mid j)}$ is the number of paths that pass through some node j other than (x, y). Please refer to (Brandes 2001, Brandes and Pich 2007, Brandes 2008) for more details.

Closeness Centrality

The closeness centrality (CC_i) of node i is the reciprocal of the sum of the shortest path distances from node i to all $(n-1)$ other nodes in the graph G:

$$CC_i = \frac{n-1}{\sum_{j=1}^{n-1} \theta_{(j,i)}} \tag{7}$$

where, $\theta_{(j,i)}$ is the shortest path distance between node j and node i and n is the number of total nodes in graph G. Closeness is normalized by the sum of minimum possible distances of $(n-1)$ since the sum of the distances depend on the number of nodes in the graph. Higher values of closeness imply higher centrality. Please refer to (Freeman 1978) for details.

Eigenvector Centrality

The eigenvector centrality (EC_i) computes the centrality for a node i based on the centrality of its neighbors. The eigenvector centrality for node i is:

$$A\, x = \lambda\, x \tag{8}$$

where A is the adjacency matrix of the graph G with eigenvalue λ. Perron–Frobenius theorem suggests that there is a unique and positive solution if λ is the largest eigenvalue associated with the eigenvector of the adjacency matrix A (Bonacich 1987, Newman 2010). Finally, degree centrality for a node is just the fraction of nodes it is connected to.

4.2.6 Other Network Properties

Some other common properties are observed in many real networks such as mixing patterns (selective linking), network homophily or similarity, degree correlations, preferential attachment, community structure, network navigation, size of giant components among others (Newman 2003).

4.2.7 Edge-level Properties

Edge Betweenness Centrality

Compute betweenness centrality for edges. Betweenness centrality of an edge e is the sum of the fraction of all-pairs shortest paths that pass through e:

$$c_B(e) = \sum_{s,t \in V} \frac{\sigma(s, t|e)}{\sigma(s, t)}$$

where V is the set of nodes,`sigma(s, t)` is the number of shortest (s, t)-paths, and $\sigma(s, t|e)$ is the number of those paths passing through edge e (Brandes 2008)

Edge Current-flow Betweenness Centrality
Compute current-flow betweenness centrality for edges. Current-flow betweenness centrality uses an electrical current model for information spreading in contrast to betweenness centrality which uses shortest paths. Current-flow betweenness centrality is also known as random-walk betweenness centrality (M. E. J. Newman 2005)

Edge Load Centrality
Compute load centrality for edges. The load centrality of a node is the fraction of all shortest paths that pass through that edge.

5. Expected Results and Specific Deliverables

We plan to complete the literature review in the next deliverable and obtain the Florida bridge and road network data to conduct preliminary network analysis. We will identify possible tools to conduct the network analysis and interpret the results. The expected future tasks are listed below:

Task 1 – Complete Remaining Literature Review
Task 2 – Obtain Accurate FDOT Road and Bridge Network Data
Task 3 – Identify the Scale and Scope of the Bridge Network to be Inspected
Task 4 – Perform Network Experiments and Analyses
Task 5 – Compilation of Results and Reporting

6. Schedule

Progress of tasks in this project is shown in the table below.

Item	% Completed
Percentage of Completion of this project to Date	20

Task No.	Task Description	2019			2020												2021		
		O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M
Task 1	Comprehensive Literature Review																		
Task 2	Obtain Accurate FDOT Road and Bridge Network Data																		
Task 3	Identify the Scale and Scope of the Bridge Network to be Inspected																		
Task 4	Perform Network Experiments and Analyses																		
Task 5	Compilation of Results and Reporting																		
			Work Performed																
			Work to be Performed																

7. References

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