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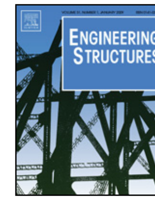

Probabilistic dynamic behavior of a long-span bridge under extreme events

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ABSTRACT

In addition to moderate wind and normal traffic scenarios, it is known that some extreme events may also occur on long-span bridges. These extreme events may include complex traffic congestion on the bridge, coupled with moderate or even strong wind. It is known that the excessive dynamic response and stress level of the bridge under these rare but critical scenarios, even for a very short period, may cause critical damage initiation or accumulation on some local bridge members. In addition to accelerating damages, the extreme events (e.g. heavy traffic) may even trigger the hazardous collapse of a whole bridge in some rare cases, especially when some hidden damage or design flaw has not been detected. Therefore, even though the extreme cases associated with congested traffic and/or windy weather are relatively rare, it is important for bridge engineers to appropriately look into these unusual extreme events during design and life-time management. By applying the general Bridge/Traffic/Wind coupled analysis methodology, the present study focuses on (1) conducting the cellular automaton (CA)-based traffic flow simulation of a long-span bridge and connecting roadways under incidental situations, (2) defining representative scenarios for the extreme events, and (3) numerically studying the bridge performance under these possible extreme events. By conducting studies on a comprehensive set of possible scenarios, it is anticipated that better understanding of extreme events of long-span bridges from the perspectives of strength and serviceability design will be achieved, which may contribute to the future design specification about long-span bridges. The proposed methodology will also offer a reasonable framework to replicate probabilistic traffic flow, characterize dynamic interaction and assess structural performance under those rare but critical situations integrally.

1. Introduction

Long-span bridges usually support a large volume of traffic and are located on oceans, grand rivers or valleys where the wind speed at a typical height of the bridge decks can be considerably high. In addition to moderate wind and normal traffic scenarios, it is known that some extreme (or adverse) events may also occur. These extreme events may include complex traffic congestion on the bridge, coupled with moderate or even strong wind. For example, severe traffic congestions may be formed on the bridge or connecting roadways as a result of an evacuation or a partial blockage of driving lanes due to traffic accidents, construction or maintenance. For hurricane evacuations, there is usually a lot of traffic passing through the bridge before the landfall of the hurricane while the wind speed may become pretty high already [1].

It is known that the excessive dynamic response and stress level of the bridge under these rare but critical scenarios, even for a very short period, may cause critical damage initiation or accumulation on some local bridge members. In addition to accelerating damage, the extreme events (e.g. heavy traffic) may even trigger the hazardous collapse of a whole bridge by breaking the "weakest link" in some rare cases, especially when some hidden damage or design flaw has not been detected. One recent example is the Minnesota bridge failure which occurred during rush hours with heavy traffic although traffic loads may not be the direct cause of failure. For slender long-span bridges, strong wind may also cause threats by working interactively with heavy traffic loads. Therefore, even though the extreme cases associated with congested traffic and/or windy weather may be relatively rare and the durations could be short, it is still important for bridge engineers to appropriately look into these unusual extreme events during structural design and life-time management of these critical infrastructures.

In the AASHTO LRFD specification [2], the only limit state similar to the scenarios discussed above is "Strength V", which is descriptively defined as "a load combination relating to normal vehicular use of the bridge with wind of 55 mph velocity". No detailed information about how the "normal vehicle use" has been defined in the specification, except for adopting the standard design vehicles as live loads. It is usually understandable as the specification was developed from and also primarily for short and medium-span bridges. For long-span bridges, it is known

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that multiple presence of heavy vehicles is very likely on long-span bridges and the simple assumption of single design truck plus lane load, or two trucks spaced at 50 ft, used in the LRFD specification [2], may not capture the worst-case scenarios of long-span bridges [3,4]. As a result, it is not clear to which extent the worst-case scenarios of long-span bridges are actually representative from the perspective of identifying critical dynamic response (e.g. displacement and stress). To understand and further capture the worst-case scenarios of dynamic response, strength and serviceability for a long-span bridge, an analytical platform, which is able to be used to appropriately replicate the extreme situations and further investigate the performance of long-span bridges, is desirable. However, to the knowledge of the writers, little study about critical scenarios of long-span bridges under extreme events can be found in the literature.

The dynamic performance of long-span bridges under wind and vehicle loads has been studied by many researchers in recent years [3,5–7]. In most existing studies, researchers either simplified the stochastic traffic flow with multiple vehicles distributed with assumed patterns [3] or modeled the traffic flow as a simplified statistical process [8–11]. Such a simplification of the actual vehicle fleet may be acceptable for short- or medium-span bridges due to the limited number of vehicles on a bridge at a time, but it has been found to be risky of causing considerable inaccuracy of the predictions for the dynamic performance of long-span bridges [5,6]. Recently, Wu and Chen [4] have applied the Cellular Automaton (CA) traffic model, originated from transportation engineering, to the simulation of the actual traffic flow through the bridge and approaching roadways. The CA-based simulation can capture the basic features of probabilistic traffic flow by adopting the realistic traffic rules such as car-following and lane-changing, as well as actual speed limits. As a result, the normal or congested traffic flow as well as incidental situations (e.g. accidents and associated lane-blockage) can be replicated with the simulated traffic flow [4]. Based on the CA-based traffic flow simulation, Chen and Wu [12] further developed a general bridge dynamic performance analytical model considering stochastic traffic and wind excitations under normal situations. After developing the analytical framework of the Bridge/Traffic/Wind coupled system, the writers also conducted numerical studies of a prototype long-span bridge under moderate wind and normal traffic flow [12].

By applying the general Bridge/Traffic/Wind coupled analysis methodology developed by the writers in the previous work [12], the present study focuses on (1) conducting the CA-based traffic flow simulation of a long-span bridge and connecting roadways under incidental situations, (2) defining representative scenarios for the extreme events, and (3) numerically studying the bridge performance under these possible extreme events. Through carrying out the studies on a comprehensive set of typical scenarios, it is anticipated that better understanding of extreme events of long-span bridges from the design perspectives of strength and serviceability can be achieved, which may eventually contribute to the future design specification for long-span bridges. The methodology introduced here will also offer a general approach for researchers and engineers to define the probabilistic traffic flow, characterize dynamic interaction and assess structural performance in those rare but critical situations for long-span bridges.

2. Cellular Automaton (CA)-based traffic flow simulation

Cellular Automaton (CA) is a microscopic traffic flow simulation technique, which has been widely used in the transportation field since it was first proposed by Nagel and Schreckenberg [13]. The cellular automaton (CA)-based traffic flow simulation model of the "roadway-bridge-roadway" system for the normal case (i.e. the driving lanes are the same for both the connecting roadways and the bridge) was introduced in Refs. [4,12,14]. Following a brief introduction of the CA-based traffic simulation for the normal case [4,15,16], the traffic flow simulation for the "blockage" situation of the "roadway-bridge-roadway" will be developed in the following.

2.1. Normal situation

The normal situation refers to the scenarios when the lane numbers of the approaching roadways and the bridge are the same. CA traffic model is to simulate the probabilistic traffic flow through discrete time and space. A lane is divided into cells with equal length along the longitudinal direction. The velocity of the vehicle is measured by the number of cells that it moves at each time step, i.e. cells/s. The rules of a typical CA traffic model include: (1) rules for vehicles moving forward on the original lane, i.e. single-lane CA model and (2) rules for changing lane, i.e. multiple-lane CA model [4].

The rules of the single-lane CA model include: (1) acceleration, (2) deceleration, (3) randomization and (4) vehicle movement [13]. These rules can be applied to the vehicles which do not intend to change the lane and keep on the original lanes. The principle of the lane-changing conditions is to allow vehicle i to drive with a higher speed without crashing with other vehicles in the target lane. The location and the velocity of vehicle i will be updated through two sub-steps: (1) *vehicle i moves to the target lane by changing transversely but without moving forward*, and (2) *vehicle i moves forward obeying the single-lane rule as introduced above*. More details about the simulation rules can be found in Refs. [13,4,12].

2.2. Blockage situation

In reality, the typical incidental cases of traffic flow are that part of a lane may be closed either on the bridge or on the approaching roadway due to traffic accidents, regular maintenance or construction. As a result, one lane of the bridge or one portion of a lane of the approaching roadway may be closed for a certain period of time. Accordingly, the bridge and the approaching roadways will have different numbers of available lanes. In contrast to the normal situation, these scenarios are referred as the "blockage situation".

A general case is that a portion of the highway (either bridge or approaching roadway) has fewer lanes than other portions (Fig. 1). As shown in Fig. 1, the leading vehicle on Lane 1 can simply regard Lane 3 as the extension of Lane 1, so vehicles on Lane 1 do not need to consider the change of the available lanes. But the leading vehicle (h2) on Lane 2 is significantly affected by the difference of the lane numbers. The vehicle h2 intending to enter Lane 3 at the next time step should obey the rules as below [17]. (1) *If the leading vehicle on Lane* 1 (h1) *intends to enter Lane* 3 *with vehicle* h2 *simultaneously, vehicle* h2 *will move to the end of Lane* 2 *first and wait for the next step*; (2) *if only vehicle* h2 *intends to move into Lane* 3 *at this time step*, *vehicle* h2 *can move into Lane* 3 *if the lane-changing rule as introduced in* 2.1 *is satisfied. As a result, vehicle* h2 *will move transversely into Lane* 1 *in the first sub-step and move forward into Lane* 3 *in the second sub-step.*

When the lane number will resume to two (i.e. from Lane 3 to Lane 4 and Lane 5) after the vehicle passes the blocked area, the head vehicle h3 on Lane 3 moves based on the following rules if it will move out of Lane 3 at the next time step: (1) *if vehicle* h3 *can keep the maximum velocity or accelerate by moving into Lane* 4, *it will move into Lane* 4 *and obey the rules of the single-lane model*; (2) *if vehicle* h3 *cannot accelerate or keep the maximum velocity by moving into Lane* 4, *it will move into Lane* 5 *if Lane* 5 *has enough space to allow the vehicle to drive faster*; (3) *if neither Lane* 4 *nor Lane* 5 *can provide the conditions to allow the vehicle to drive at the desired speed, vehicle* h3 *will move into the lane which can allow for a larger velocity*.