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Smart Technologies for Health Assessment and Monitoring of Infrastructure Components

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Abstract: Governments' and other reports indicate the critical state of disrepair of the infrastructure and call for urgent actions. Delaying prompt actions implies catastrophic failures and probable human loss. The technological assessment and/or monitoring of the infrastructure components is one of the means to reduce the vulnerability of those systems. This approach is essential in any urban development in general and in particular when sustainability is required. Data about the health of a system is always required for engineering calculations. Nonetheless, the true conditions are challenging in many situations because of the complexity of geometry, framing systems, detailing of connections, workmanship, etc. This paper presents smart technologies to reliably assess the health condition of three selected infrastructure components: utility poles, connections, and falling impacts. The presented technologies are based on the rigorous engineering fundamentals and are demonstrated using digital tools.

Keywords: *Connection, Dynamic, Inspection, Falling, Impacts, Nondestructive, Poles, Soil, Strength, Structures, Vibration, Utility*

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I. INTRODUCTION

1. Utility Lines

Utility lines are vital components of infrastructure and the wide spreading urbanization because of the unprecedented changing world. They involve different pathways, components of variable strength and switching mechanisms. If ignored, the rupture of poles may disrupt the normal societal function and lead to human mortality. To elaborate, the North American utilities have more than 150 million poles in service for electricity transmission and distribution estimated at a replacement value of $50 billion. Estimated more than 3 million new poles are installed each year with an estimated replacement cost of $1,500 to $8,000 per pole. Consequently, incorrect decisions to replace prematurely poles can cost the industries at least $4,500M to $24,000M in losses.

2. Connections

In any engineering analysis of framed systems, the stiffness of the connections are required. In retrofitting projects, the determination of the true stiffness is a challenging task. This paper tackles the challenge. Complex framing systems, member properties, material properties, environmental conditions, accessibility, and other factors compound the complexity of this challenge.

3. Falling Impact

Falling incidents represent the largest single cause of fatality in the workplace. In general, the falling events occur each year in thousands. The statistics indicates that 32% of the falling incidents resulted in casualties. Other ramifications of falling include the huge cost to employers, the legal penalties to companies, physical and psychological human impairment, etc. Smart analytic tools to scrutinize objects fall-related incidents are thus essential to assess their impacts. The available literature indicates that such tools yet to be developed. This paper presents in part an approach in reply to the needs in this area. It aims at gaining the insight into the concept, mechanism and impacts of falling by quantify the effects of the possible variables that highlight the incidents.

II. SMART TECHOLOGICAL APPROACHES

1. Utility Lines

1a. Analytic Formulation

The theory presented here is based upon the fact that defects or damages affect the vibration characteristics of poles. By examining how poles vibrate, location and size of defect, and strength could be characterized. The equilibrium equation of forces and moment of a pole element is as follow

$$\frac{\partial V}{\partial x} + m\,\frac{\partial^2 y}{\partial t^2} = p(x,t) \qquad (1)$$

in which V = Shear force; p = Applied load; m = Mass per unit length; x = Distance along the pole; t = Time. Using the fundamental bending moment-shear and bending moment-curvature relationships, the following governing equation is obtained

$$EI\,\frac{\partial^4 y}{\partial x^2} + m\,\frac{\partial^2 y}{\partial t^2} = p(x,t) \qquad (2)$$

in which y = Displacement of the pole at distance x; E = Modulus of Elasticity; I = Moment of inertia. The solution of

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the above governing differential equation may be obtained in various mathematical ways, one of which is to use the separation of variables as follows

$$y = \emptyset(t)\,\emptyset(x) \qquad (3)$$

Substituting Eq. 3 into Eq. 2 yields the following equation

$$EI\,\frac{\partial^4\emptyset(x)}{\partial x^4}\,\emptyset(t) - m\,\omega^2\,\emptyset(x)\emptyset(t) = p(x,t) \qquad (4)$$

in which ω is the natural frequency of the pole and ϕ is its mode shape. Equation 4 can be re-written for the parts of the pole above and below ground as follow

$$EI\,\frac{\partial^4\emptyset(x)}{\partial x^4} - m\,\omega^2\,\emptyset(x) = 0 \qquad (5)$$

$$EI\,\frac{\partial^4\emptyset(x)}{\partial x^4} - (m\,\omega^2 + k)\,\emptyset(x) = 0 \qquad (6)$$

in which k is the soil modulus. Solutions for Eqs. 5 and 6 may now be obtained using one of the known and tested for reliability numeric methods.

1b. A digital assessment tool

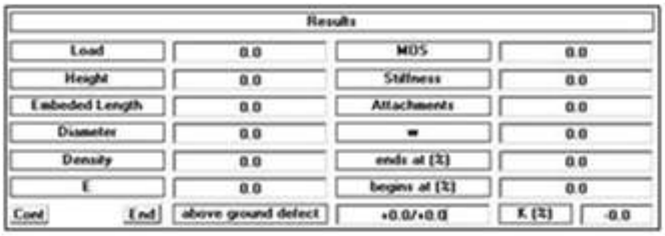

Figure 1. A Screenshot of the developed digital tool for the presented analytic approach

Digital tools are used nowadays in each facet of humans' life. Figure 1 shows a typical screen for the presented vibration-based methodology. The data about geometric, material, soil, and attachment if any are required. The figure also shows the numeric results such as the location and size of the defect, whereabouts; above and/or below ground, and the status of strength.

1c. Numeric Results

Table 1. Comparison of results obtained using the presented technology and FE

DEFECT (%)		FREQUENCY		
Begins at	Ends at	F.E.	DADPOLE	%
95	100	35.9	36.3	1
90	100	23.4	23.7	1
58	70	42.6	43.0	1
ideal pole with overhead		118.3	118.2	0

The accuracy and level of confidence in using the vibration-based approach highlighted above were measured in various ways. The analytic method was used to predict the status of poles for which analytic solutions are available in the literature. It was also used to solve several problems, the solutions of which were previously obtained by the author using the finite element (FE) method. Excellent agreements have been noted as indicated by discrepancies of less than 1% at best among the different results as shown in Table 1.

1d. Onsite Procedure

Generally, a pole could be tapped to induce a vibration, though it is vibrating at all times because of the surrounding environment. The signal is then recorded and analyzed. The result is subsequently integrated with the presented analytic method, the solution of which will lead to location, size, whereabouts of defects, and status of strength. This assessment process can all be completed on site without removing any parts of the pole or using laboratories. The entire process is fast to conclude in any weather condition and on any soil.

1e. Conclusions

From the day they are set up, utility poles made of any material are subject to wide range of harsh environmental and natural attacks. Damages are most often concealed in the pole escaping detection from the outside on site. The result is a loss of characteristics that are essential for the survival of poles and the high potential of pole failure. Based on the available knowledge, it was reported that poles can be contaminated or damaged, and locations of defects can easily be missed. This reality was confirmed in testing a large number of real poles. That study concluded that none of the available methods was sufficiently accurate for predicting strength of poles or meet the pole reject requirements. This procedure presented in this paper overcomes some of the shortcomings of other methods. The suggested analytic approach doesn't extract samples, thus eliminates potential biological contaminations leaving the poles undamaged. It incorporates soil without needs for excavation that disturb the soil condition, attachments. The analytic theory applies well established and tested rigorous fundamentals, thus avoids potential errors. In this way, the health status, i.e. defects location and extent as well as strength, of utility poles could be assessed in a smart technological procedure. Finally, some numerical results have been presented to demonstrate the accuracy and level of confidence in using the presented theory.

2. Connections

2a. Analytic Formulation

Connections in framed systems are neither pins nor ideally rigid as commonly assumed. Flexible connections provide a suitable approach to assess the actual stiffness of connections. Consider a frame element with end rotational stiffness K_i and

K_j where i and j designate the ends. Its stiffness $[K]_{6x6}$ and consistent mass $[M]_{6x6}$ matrices are already obtainable from many references in the literature. These matrices include the following parameter C_i

$$C_i = \frac{L\,K_i}{E\,I + L\,K_i} \qquad (7)$$

in which L and I are the member length and moment of inertia, and E is the modulus of elasticity of its material. The equation of motion for free vibration of this element and its vibration characteristic value equations are

$$[M]\,\{\ddot{x}\} + [K]\,\{x\} = 0 \qquad (8)$$

$$|[K] - \omega^2\,[M]| = 0 \qquad (9)$$

in which x is the displacement and ω denotes the natural frequencies of vibration. The solution of Eq. 9 can be obtained backward; i.e. obtain an input that would result in the given input. This is achievable by defining the state and objective of the equation, and provoke an iterative search to reduce the difference between the two. In general, a solution is found through trial and improvement iterative procedures.

2b. Onsite Procedure

In typical assessment projects, the cross-sectional moment of inertia and the modulus of elasticity of the member material need to be determined. Next, the vibration signal of frame element are measured and recorded using a signal conditioner. The recorded signal can then be analyzed to obtain the fundamental frequency ω. Equation 9 can finally be solved as described previously for the connections stiffness K_i and K_j. This procedure has been analytically verified on a number of cases with known solutions. This study is still in progress for further development, but the obtained results are satisfactory to plan for the next phase with a broader scope than the one described.

2c. Conclusions

This paper proposed a technological approach to assess the rotational stiffness of structural frame members. The approach is useful for retrofitting structures in the aging infrastructure. Once the vibration signals from a frame are measured and analyzed, a reverse engineering algorithm could be used to solve the vibration characteristic equation for the required stiffness. The required hardware and software are readily available and inexpensive.

3. Falling Impact

3a. Analytic Formulation

An analytic model that simulates the structural performance and responses of components, as ladders or scaffolds, under the impact of falling objects is introduced. The model is based upon deriving the differential equations for the dynamic motion and then solving them. The sequence of falling in an incidence includes three phases. First, a free fall is triggered by initial conditions, based upon which the falling object may impact the component within its length at a lower level. Both the component and the falling object may then move with different kinetics till hitting the ground. The location of its center of mass, and the mass moment of inertia, I_L can be determined from the geometric and physical properties of the components. An equivalent uniform rigid bar can then represent the component. Because the component and its equivalent bar have identical mechanics characteristics

$$L_{equivalent} = \sqrt{\frac{12\,I_L}{m}} \qquad (10)$$

in which $L_{equivalent}$ is the length of the equivalent uniform bar and m is the mass of the original or equivalent component. The equations of motion can now be derived using Newton's laws. In this formulation, the forces are the weights of bar and object, and constraints forces. The former forces are known whereas the latter ones are unknowns. By eliminating the unknown forces, the governing equation is

$$\alpha = \frac{K_1\,K_2}{K_3}\sin\theta \qquad (11)$$

in which α = Angular acceleration, rad/s^2; K_1 = (1.5 g / $L_{equivalent}$) where g is the gravitational acceleration; K_2 = (1 + 2 W_r D_r); K_3 = (1 + 3 W_r D_r^2); W_r = Ratio of weight of the falling object to that of the bar; D_r = Ratio of impact distance of object from the base to the height of the bar; θ = Angle of the component from the vertical. This second-order differential equation has no closed form solution and must be solved numerically to obtain the response history; that is θ-t relationship where t is the time. However, a partial integration can be achieved, from which the angular velocity ω is given by

$$\omega = \sqrt{\frac{2\,K_1\,K_2\,(\cos\theta_o - \cos\,\theta) + \omega_o^2}{K_3}} \qquad (12)$$

in which the subscript o stands for the initial condition. Equations 11 and 12 were integrated using the fourth-order Runge-Kutta method with various integration step sizes. After Eq. 11 has been solved, any other quantities of interest such as forces can be determined. In a typical integration process, the required data constitutes the height of component, the position of object on the bar, the weights of bar and object, the initial angle of inclination and the desired final angle. The range of the latter is from zero to 90 degrees. The output has a large number of quantities such as the times to impact the bar and the ground, the position of impact on the bar, the angle of impact with the bar, the impact forces on the object from the bar and ground, and the ratio of impact forces and standard test values which could be obtained from manufacturers. It is worth mentioning that because the fundamental principles of engineering mechanics; upon which this paper is prepared, have not changed in centuries; only the original equations are presented throughout the paper.

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3b. Numeric Results

Fig. 2 A Snapshot of the Digital Tool for Falling Impact

The iterative nature of the described numeric solution has called for the use of computer applications. The mathematic operations were implemented using Windows-based tool as shown in Fig. 2. A typical output presents the position of object impact with components, the times of fall to ground, the direction of hitting the component, the impact force with components, and the impact force with ground.

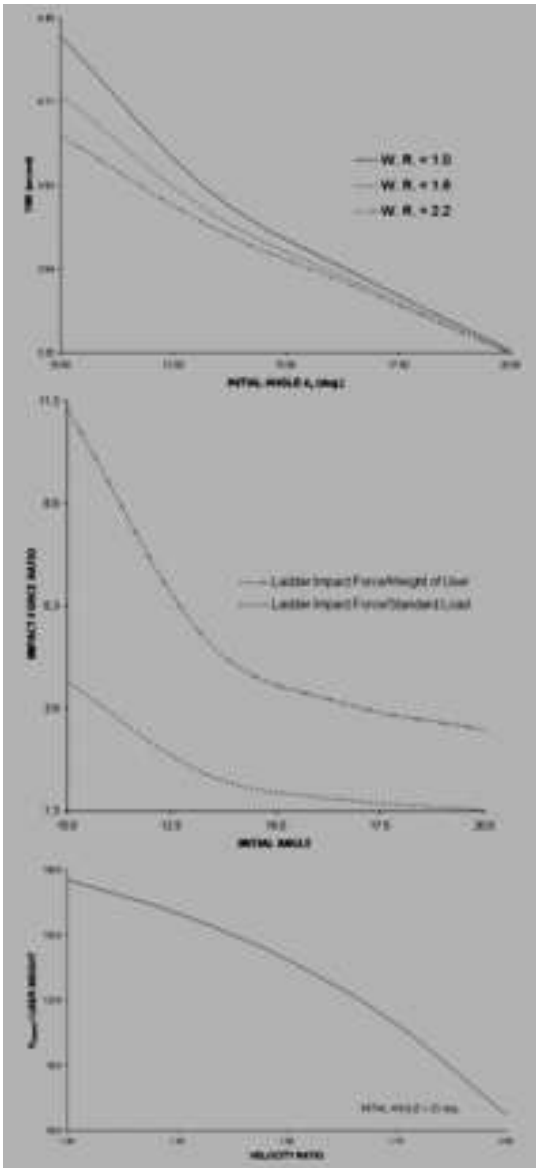

Fig 3 Numeric Results

Figure 3 shows the effects of the bar inclination angles on the falling time to ground, the impact forces on the object and bar at the times of hitting with the bar, and the way the falling object fall. The numeric results were obtained usin L = 60 ft, W_{object}/W_L = 1, 1.6 and 2.2.

3c. Conclusions

An analytic model was introduced to evaluate each falling incident against a range of criteria as configuration and physical properties, falling conditions as well as characteristics of objects. The numerical procedure adopted in this article is general and can accommodate a wide range of numeric values for the variables. This model could investigate the fatality of incidents and their causes; quantitatively determine what, why and how incidents take place; and determine the level of physical hazard, and the structural damages.

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