A COMPUTER SIMULATION OF AN ALTERNATIVE DESIGN TO TREE CROWN SUPPORT SYSTEMS

By Craig M. Greco[1], Andy Lee[2], Donald Ham[3], E. Thomas Smiley[4], and E. Harry Law[5]

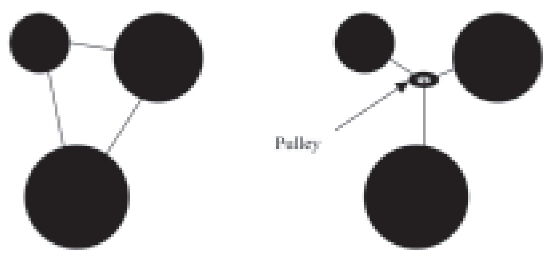
Abstract. Trees with multiple leaders that are susceptible to breaking pose a serious threat to nearby people and structures, and compromise overall tree health and aesthetics. The traditional remedy has been to install flexible steel cables in the crown of the tree in an attempt to limit the displacement of the leaders. This project was conducted to evaluate an alternative three-leader support cable system using computer simulation. The system is centered on a pulley that redirects loads along convergent cables, allowing for more displacement of the cabled leaders while minimizing the amount of materials and time required for installation. Comparisons between the traditional system and the alternative design were simulated using two-dimensional computer modeling to quantify the forces on the cables. The test winds were standardized at 43.45 km (27 mi) per hour for duration of 2 seconds. An interval of 18 seconds was allowed for the system to return to equilibrium for a total trial time of 20 seconds. Each system was standardized for cable diameter, damped springs, and distance between leaders with only the total length of cable varying according to the requirements of each system. Results demonstrated a significant decrease in both overall and shock forces to support cables when utilizing the alternative design. The decrease in force (based on cable configuration and wind direction) ranged from a 3.4:1 to 22.4:1 for the alternative and traditions systems, respectively.

Key Words. Cabling; canopy support systems; loads; displacement; computer modeling.

Tree leaders, arising from crotches with included bark that are susceptible to breaking, pose a risk to targets near the tree and compromise the overall health of the tree (Smiley 2003). Traditional remedies for these problems have been to install flexible steel cables in the crown of the tree in an attempt to stabilize leaders that are at risk of breaking. New stabilization materials, systems, and attachments have been developed within recent years, spurring an interest in alternative canopy support systems (Stobbe et al. 2000).

Current standards in arboriculture aimed at managing trees at risk for breaking rely on flexible steel cables that are installed within a tree crown to limit excessive movement and reduce stress within a weak crotch (ANSI 2000). Traditional cabling design and installation practices are based on the work of Thompson (1959). Further investigations into support systems are sparse, limited to utilization of a belt stabilization system, and tree cable forces (Stobbe et al. 2000.

Despite efforts to preserve canopy integrity with traditional cabling support systems, failures can occur where the systems have had excessive wear, were installed wrong, or have not been properly maintained. Additionally, installation of traditional three-way systems is challenging and requires stringent adherence to proper installation techniques to be effective. Tension forces within the traditional support system design are likely unbalanced and extreme, leading to component deterioration and greater inspection and maintenance requirements. In an effort to address these shortcomings, an alternative crown support cabling system for three leaders, utilizing a central pulley to balance loads, was proposed (Figure 1). The objective of this investigation was to evaluate and compare the traditional cabling system for supporting three leaders with the alternative "pulley" design.



Traditional System: Three separate cables, oriented parallel to the ground, are fastened to leaders within the crown of the tree.

"Pulley" System: Two cables and a pulley, oriented parallel to the ground, are installed. One cable fastens to a leader and the pulley. The second cable runs through the pulley and is fastened to the other two leaders.

Figure 1. Traditional triangular support system and alternative system.

MATERIALS AND METHODS

In traditional triangular support systems, cables are installed at slightly different heights within the crown. Because of this design element the structural integrity of the support system is sub-optimal. Furthermore, because traditional triangular support systems are difficult to install, the integrity of the tree itself could be jeopardized due to the unfavorable loads introduced by an incorrectly installed support system. The alternative system employs a unified design that is installed in a single plane uniformly parallel to the ground thus utilizing the linear strength of the assembly.

A computer simulation program was used to compare the cable tension using two tree support system designs. To eliminate confounding variables such as environmental factors, material defects, installation error, shape and size of canopy, and distance between and diameter of leaders, the evaluation was accomplished with a two-dimensional animation simulator program *Working Model 2D* version 5.0 for Windows 98 (Knowledge Revolution, San Mateo, CA). This program applies Newtonian mechanics to a user-designed model. It can accurately compute the dynamics of a system and is widely used in engineering to evaluate constraints and forces of simple systems.

Both the traditional and alternative systems were constructed and compared with *Working Model 2D*. The solid circles in the figures represent "equivalent" leaders, while the solid lines connecting them represent the various cabling systems. The bending stiffness of each leader was modeled by an equivalent linear spring, which acts to oppose displacement of the leader in any direction (springs act to return the system to equilibrium). Structural damping of the leaders acts to make motion decay with time and was modeled by equivalent linear viscous dampers parallel to the springs. The restoring force of a simple linear spring may be expressed as $F = k(x)$, where x is the displacement, k is the spring constant (with units of N/kg), and F is the restoring force in N. The damping force of a linear viscous damper is given by $F = c(dx/dt)$, where c is the damping constant in N(sec/cm), and dx/dt is the instantaneous velocity across the damper with units of cm/sec.

Generally, in order for mechanical oscillation to occur, a system must possess two qualities: elasticity (the bending stiffness of the leaders) and inertia (mass of the moving leaders). When the system is displaced from its initial position, the elasticity provides a restoring force such that the system tries to return to equilibrium. When displaced, the mass of the leaders, or the inertia of the system, causes the system to overshoot equilibrium. This constant interplay between elasticity and inertia is what allows oscillatory motion to occur. The natural frequency of oscillation is dependent on the elasticity and inertia of the system. An oscillatory motion whose frequency decays with time is termed "damped oscillation."

Each cable was modeled using the "rope tool" from *Working Model*. The rope tool prevents the leaders from separating by more than a specified distance (i.e., the specified length of the rope). Ropes will go slack when the leaders move closer together than the length of the rope. The lengths of the ropes were chosen such that the cables were taut but sustained no tension in their equilibrium configuration.

For each of the two systems, three different triangular configurations (Figure 2) were evaluated with simulated winds from eight directions (Figure 3). Simulated leader sizes and constraints to their movement are listed in Table 1.

The simulated leader sizes were chosen as representative of those found in landscape trees. The values of the springs, dampers, and equivalent masses of the model determine the natural frequencies and response to external excitation (i.e., in this case, wind) of the system (Thomson and Dahleh 1998). The values used in the simulation were chosen on the basis of experience to give time histories of the response of the system that were deemed representative of actual trees.

Simulated wind forces representing an approximate wind speed of 43.45 km (27 mi) per hour were used. This speed was selected because the Beaufort scale indicates that a wind speed of 43.45 km per hour is necessary to cause movement of large branches (Cullen 2002). The wind force lasted for 2 seconds. Preliminary trials indicated that the system returned to equilibrium in approximately 18 secondsafter the wind ended. Each system was standardized for cable diameter, damped springs, and distance between leaders, with only the total length of wire rope varying

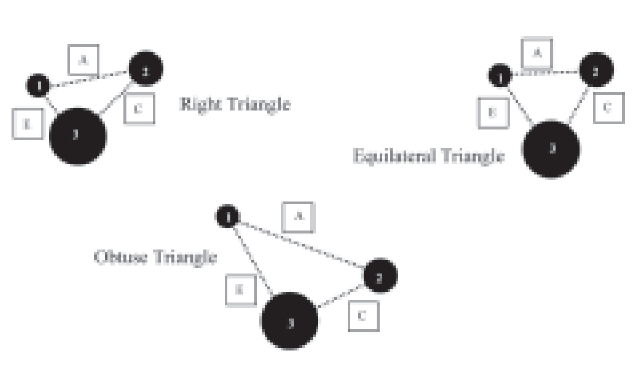


Figure 2. Three triangle configurations, representing different leader configurations found within a tree canopy, evaluated with simulated winds in *Working Model 2D*.

Table 1. Values of parameters of the simulated system.

Parameter	Leader #1	Leader #2	Leader #3
Leader diameter	17.78 cm (7 in.)	30.48 cm (12 in.)	45.72 cm (18 in.)
Spring	4.30 kg/cm (9.5 lb/in.)	8.07 kg/cm (17.8 lb/in.)	12.97 kg/cm (28.6 lb/in.)
Damper	0.009 kg (s/cm) 0.02 lb (s/in.)	0.18 kg (s/cm) 0.04 lb (s/in.)	0.027 kg(s/cm) 0.06 lb (s/in.)
Leader weight	5.26 kg (11.6 lb)	10.52 kg (23.2 lb)	21 kg (46.3 lb)

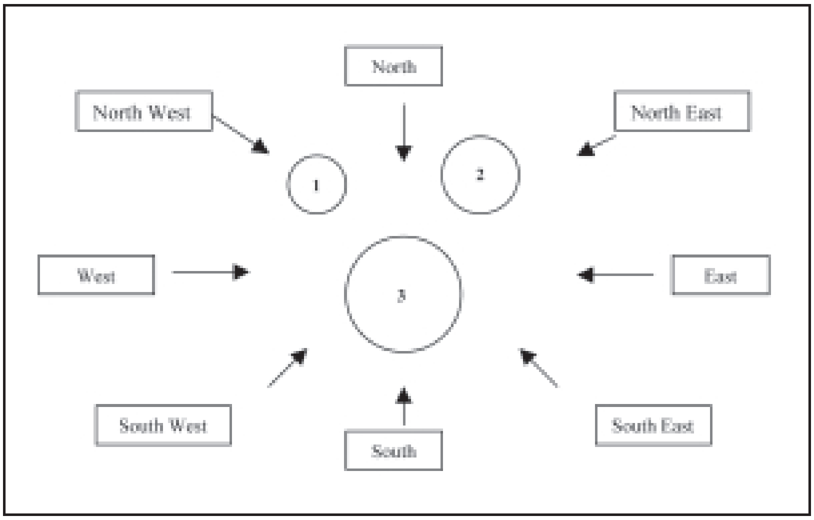


Figure 3. Diagram of the relative leader diameters and directions from which the simulated wind forces were applied.

according to the requirements of each system. Wind-burst forces were applied from eight directions to each of the three triangular configurations as graphically represented in Figure 3. To prevent potential exaggeration of peak readings, all spring and damper pairs were then rotated 45 degrees, and wind-burst forces were repeated from the same eight directions for a total number of 16 trials for each configuration.

RESULTS AND DISCUSSION

The computer simulation found a significant reduction in peak values of cable tension for the alternative system when compared to the traditional system. Peak tension forces were reduced by a factor of 8.3 for the right triangle configuration, a factor of 1.1 for the equilateral triangle configuration, and a factor of 3.0 for the obtuse configuration (Figure 2). It is notable that in all cases, the total system tension of the alternative design is less than not only the sum of cable tensions in the current system, but less than the highest individual cable tension in each case (Table 2).

Figure 5 shows the instantaneous configurations of the two systems during the dynamic response to the wind force input. It also shows the time histories of the forces in the two cable systems. The plot on the left side of the alternative system graphic shows the tension in the cable that connects the two northernmost leaders. For the traditional system, the top plot shows the tension in the north cable. The lower lefthand plot shows the tension in the cable connecting the west side leaders, and the lower righthand plot shows the slack east side cable.

Note that the displacement values of the leaders for the alternative system are smaller than those of the current system. It is also interesting to see that one of the cables in the current system has become slack. One might expect a large shock load being transferred to the leaders when it becomes taut. For all trials of both systems the cable tensions decayed to their equilibrium (zero) values in less than 16 seconds (Figure 5). Figure 5 also shows that the alternative system displays a lower frequency of oscillation and a decrease in damping.

By incorporating a central pulley, peak cable tension is reduced and overall forces are damped and redirected throughout the entire system. After the wind force is removed, the alternative system exhibits smaller amplitude motions of the leaders. The deflections and rates of deflection of the leaders are proportional respectively to the forces in the spring and damper units, which, in turn, represent the bending stiffness and damping of the leaders. This result is a very important one because the bending stresses in the leaders are proportional to these forces. In actual trees, large bending stresses can lead to fracture of the leaders. This indicates the improved constraining action of the alternative system.

Location and lengths of cables are other factors that may contribute to the differences in the cable tensions for the two systems. For the trials conducted, the shortest cable lengths usually resulted in the largest cable tensions.

Table 2. Individual cable tension loads in the three triangular shapes. Numbers are individual cable tensions in pounds after the 20 second simulation was over, with an applied force equivalent to a wind load of 43.45 km (27 mi) per hour.

	Right triangle configuation				Equilateral triangle configuration				Obtuse triangle configuration			
Direction of force	Alt. system	B	A	C	Alt. system	B	A	C	Alt. system	B	A	C
N	0	0	0	177.92	0	0	35.58	0	0	0	0	0
NE	0	0	0	306.92	0	31.13	427.02	0	0	0	298.03	0
E	2	0	498.20	404.78	0	84.51	587.16	0	0	0	275.78	0
SE	26.68	22.24	1435.44	17.79	636.09	733.95	413.68	271.34	289.13	1227.70	1436.77	17.79
S	0	573.82	908.32	0	618.30	676.12	0	515.99	475.95	507.09	911.88	0
SW	80.06	827.36	105.12	0	182.37	431.47	0	805.12	409.23	115.65	106.75	0
W	173.48	569.37	0	0	0	0	0	484.85	71.17	0	0	0
NW	0	0	0	0	0	0	0	0	0	0	0	0

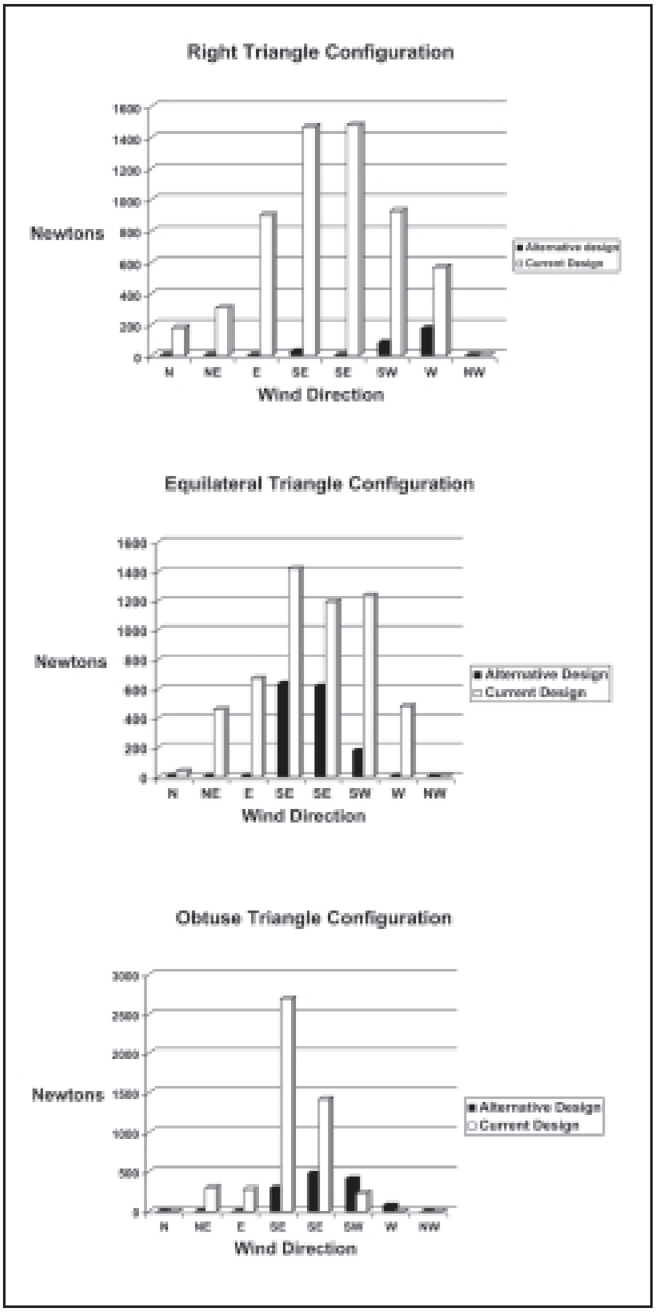


Figure 4. These graphs represent the sum of total system tension of the alternative design as it compares to the sum of cable tensions in the current system.

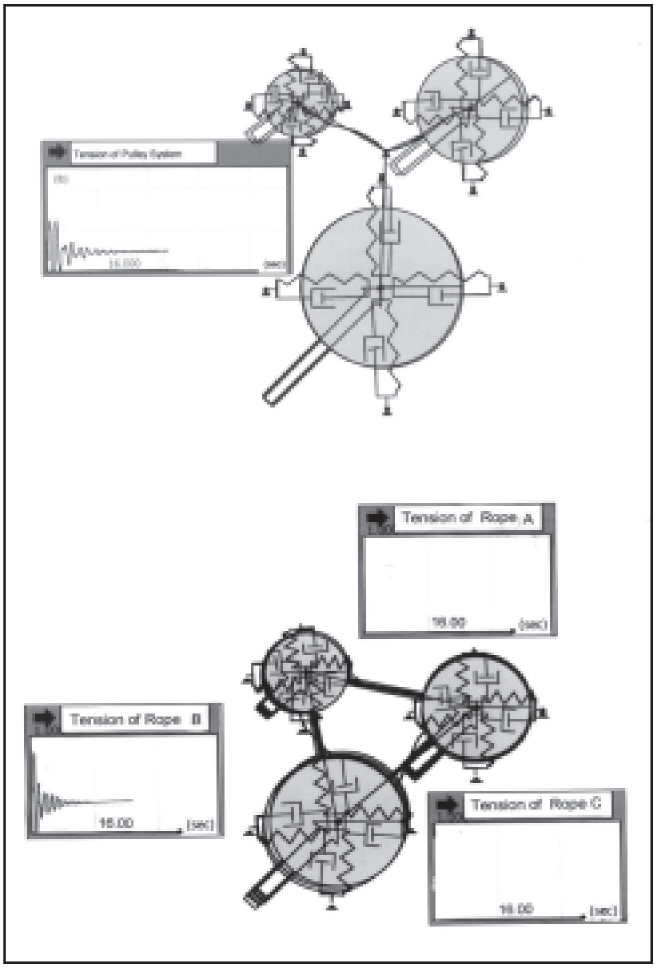


Figure 5. Comparison of the two systems at an instant during the 20 second trial.

In traditional system, each cable is fastened to adjacent leaders; thus, occasionally overconstraining the system. As the leaders attempt to displace independently within the traditional system, the cables are subject to greater shock loading. While the intent of the system is to restrict excessive displacement to the leaders, it sometimes results in strong forces that create instances of cable slack followed by jerking movements of the cables or the leaders themselves. These movements can cause additional tension within the system and damage to or excessive loading on the tree or hardware.

With the integrated design implemented in the alternative system, absolute and relative displacements of the leaders are controlled. The alternative design eliminates much of the shock loading by creating an integrated system allowing for less restriction and more favorable movement of the leaders. These results suggest that leaders actually cabled in this manner would move in a more fluid manner with smaller displacements and return to equilibrium more quickly.

A direct correlation was found between force direction and leader size. The values of tension recorded for each cable are listed in Table 2.

Here, the majority of the larger cable loads were recorded when the force was directed from the southeast, south, and southwest, where the larger leaders are positioned. Conversely, smaller cable loads correspond to wind forces from the north and northwest, where smaller leaders lie. This pattern certainly suggests that when a force is applied first to the smaller of the two leaders, the system collapses-therefore allowing more cable slack and displacement to the largest of the leaders. When the opposite occurs, the largest leader is not as easily displaced as the smaller leaders, resulting in less tension being transferred to the cables.

CONCLUSIONS

Computer simulation has evolved into a powerful tool that allows the user to create and evaluate alternative designs for systems in a short amount of time. The objective of this investigation was to evaluate and compare the traditional system for supporting three leaders with the alternative design using a computer simulation. These results indicate that the alternative crown support system would allow for more controlled displacements of the cabled leaders while optimizing location of installment and minimizing the amount of materials and time requirements necessary for installation.

The alternative system is easier to install because fewer anchors and cables are required and should increase the longevity of the cabling system due to lower peak stress. Results also indicate that the forces imposed on the leaders would be significantly reduced, thus reducing potential failure of the leaders.

However, specifications for pulley size and construction for the alternative system are unknown and appropriate testing would be required prior to installation in trees. The values chosen for the spring and dampers—the devices used to simulate the actual stiffness and energy dissipation properties of the leaders, were such as to represent the observed motions of most trees subjected to the wind loadings of the magnitudes used. Foliar loads were not included during the test simulations in order to eliminate a potentially unpredictable confounding variable, but could have a considerable impact on results of field trials.

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[1*]*Graduate Student*
Department of Forestry and Natural Resources
Clemson University
Clemson, SC 29634-0317, U.S.
580 Curry Springs Place
Hamilton, VA 20158, U.S.

[2]*Professor of Forest Products*
Department of Forestry and Natural Resources
Clemson University
Clemson, SC 29634-0317, U.S.

[3]*Professor Emeritus*
Department of Forestry and Natural Resources
Clemson University
Clemson, SC 29634-0317, U.S.

[4]*Arboricultural Researcher*
Bartlett Tree Research Laboratory
13768 Hamilton Road
Charlotte, NC 28278, U.S.
and
Adjunct Professor
Clemson University
Clemson, SC 29635-0317, U.S

[5]*Alumni Distinguished Professor*
Department of Mechanical Engineering
203 Fluor Daniel EIB
Clemson University
Clemson, SC 29634-0921, U.S.

**Corresponding author.*

Zusammenfassung. Bäume mit mehreren Leittrieben sind brechanfällig und stellen daher eine ernsthafte Bedrohung für Publikum und Strukturen dar, und sind ein Kompromiss für Baumgesundheit und –ästhetik. Die traditionelle Methode bestand darin, flexible Stahlseile in der Krone zu installieren um die Entfernung dieser Triebe zu limitieren. Dieses Projekt wurde durchgeführt, um ein alternatives Kabelsystem zur Unterstützung von drei Leittrieben unter Verwendung von Computersimulationen zu bewerten. Das System wird auf eine Rolle konzentriert, die Lasten an konvergierende Kabel umleitet, mehr Spielraum für die Verdrängung von verkabelten Baumtrieben bietet und gleichzeitig den Aufwand an Material und Zeit für die Installation minimiert. Die Vergleiche zwischen dem traditionellen System und dem alternativen Design werden mit Hilfe zweidimensionaler Computermodellen simuliert, um die auftretenden Kräfte an den Kabeln zu quantifizieren. Die Ergebnisse demonstrieren einen signifikanten Abfall sowohl der Gesamtkraft als auch der Schockkraft um die Kabel unterstützen, wenn das alternative System angewendet wird. Der Kraftabfall bei beiden Systemen (basierend auf Kabelkonfiguration und Windrichtung) rangierte zwischen 3.4:1 bis 22.4:1.

Resumen. Los árboles con múltiples líderes que son susceptibles a la rotura crean un serio riesgo a la gente cercana y a las estructuras y comprometen la salud y la estética de los árboles. El remedio tradicional ha sido instalar cables de refuerzo en la copa del árbol como un intento de limitar el desplazamiento de los líderes. Este proyecto fue conducido para evaluar un sistema alternativo de soporte usando simulación con computadora. El sistema está centrado en una polea que redirige las cargas a lo largo de cables convergentes, permitiendo mayor desplazamiento de los líderes cableados mientras minimizan la cantidad de materiales y tiempo requerido para la instalación. Las comparaciones entre el sistema tradicional y el diseño alternativo fueron simuladas usando dos modelos de dos dimensiones por computadora para cuantificar las fuerzas sobre los cables. Los resultados demuestran una disminución significativa tanto en el total como en las fuerzas que soportan los cables cuando se utiliza el diseño alternativo. La reducción en la fuerza (con base en la configuración del cable y la dirección del viento) estuvo entre 3.4:1 a 22.4:1 para los sistemas tradicional y alternativo, respectivamente.

Résumé. Les arbres avec des flèches terminales multiples qui sont susceptibles de se briser posent un risque sérieux pour les gens et les infrastructures à proximité ainsi que compromettent la santé générale des arbres et leurs qualités esthétiques. Le remède traditionnel a été d'installer des haubans flexibles dans la cime de l'arbre afin de tenter de limiter la cassure des branches principales. Ce projet a été mené dans le but d'évaluer une alternative au système de support traditionnel au moyen de câbles d'acier, et ce au moyen d'une simulation informatique. Ce système est centré sur une poulie qui redirige les forces le long de câbles convergents, ce qui permet plus de mouvements pour les branches principales câblées tout en minimisant la quantité de matériel et le temps requis pour l'installation. Des comparaisons entre le système traditionnel et le design alternatif ont été simulées au moyen d'un modèle informatique bidimensionnel afin de quantifier les forces sur les câbles. Les résultats ont démontré une diminution significative, à la fois au niveau des forces globales que des coups sur les câbles de support lorsque le design alternatif était utilisé. La diminution des forces, en se basant sur la configuration des câbles et la direction du vent, allait de 3,4:1 à 22,4:1 entre les systèmes alternatif et traditionnel respectivement.