Diagonally Operating Knotted Overlay (DOKO) Structural System

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Abstract – *Diagonally operating knotted overlay (DOKO) is a structural system inspired from the container like hand-woven conical or frustum shaped structure known as Doko. Doko is made from bamboo strips and is generally used for carrying goods, and for harvesting and storing crops in South East Asia mainly in Nepal, Bhutan, and Northern India. Doko normally carries load that is about a hundred times greater than its weight. The considerably higher load carrying capacity to weight ratio is due to all of its parts/components contributing to supporting the load. This enables in saving construction material and at the same time achieving higher structural efficiency. The structural mechanism of the Doko can be most closely observed as the combination of external bracing and outrigger system forming diagonally operating knotted/woven overlay referred here as the DOKO structural system. In this article, the implementation or application of the DOKO system to building structural systems along with its probable structural, economic, and environmental benefits and challenges are discussed. Furthermore, a comparison of the structural performance of buildings with DOKO system and conventional systems such as moment-resisting frame, shear wall and the dual structural system is achieved through lateral load analysis of building with these structural systems. Compared to conventional systems, it is found that the DOKO structural system is highly efficient in establishing stability in the building against lateral forces.*

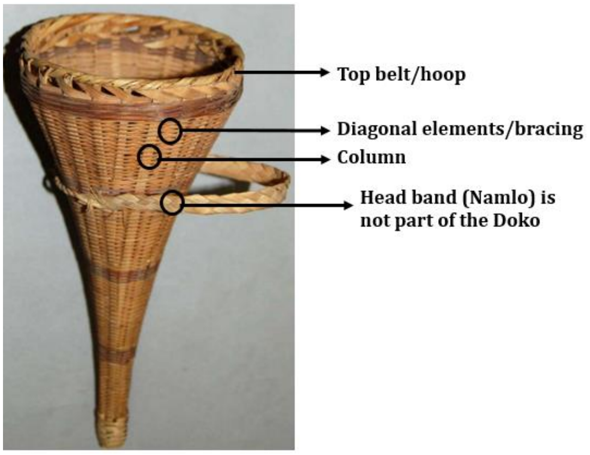
***Key Words*: sustainable structural system, lateral stability, diagonal bracing, outrigger structural system, core wall system, suspended floors, flexible façade, seismic and wind resistance, low medium and high-rise buildings**

1. Introduction

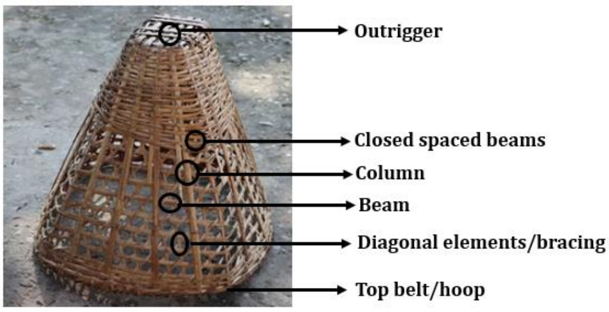
The conventional building structural system which uses multiple shear wall or core walls are becoming less functional in the modern days of building design. As the buildings are becoming more slender or smaller in plan and larger in height, using these multiple walls for lateral stability affects the net habitable or rentable area, prohibit the provision of large column-free space, and increase the building's seismic mass. Moreover, these walls generally create strength eccentricity that amplifies the seismic actions and vulnerability in the building [1]. The author believes that these issues can be resolved by adopting a "diagonally operating knotted overlay (DOKO)" structural system. There are also other valuable benefits of this system. The structural robustness, material efficiency, and suitability to modular and automated construction techniques of the DOKO system make it beneficial to building with all ranges of size and heights. Similarly, it offers quick construction of the building as well as a façade system. Additionally, this system can be used for designing and constructing tilted or rotated buildings and buildings with energy-efficient envelopes.

The DOKO structural system proposed in this article is intended to emulate the structural benefits of the conical or frustum shaped structure known as Doko. Doko is used for carrying goods and for harvesting and storing crops in countries of South East Asia for a very long time with the documented photographic evidence to 1793 AD [2]. The terminology DOKO coined by the author is not to be confused with the term Doko that is presented in this article. The term DOKO refers to the building structural system proposed by the author while Doko refers to the basket-like container used to carry goods. Based on the author's experience, the Dokos made from bamboo are about two to five kilograms in weight and can carry up to two hundred kilograms of goods with negligible deformation. However, the well-built Doko may only fail with a failure load of about a ton. This mean, it can carry a load that is more than a hundred times its weight. The considerably higher load carrying capacity to weight ratio is due to light construction material, structural configuration allowing all the structural elements to carry and transfer load and also contributing to minimising the amount of material needed. This motivated the author to assess the structural benefits of this system and its applicability to building structural systems.

The Dokos are mainly of two types: conical and frustum shapes. The frustum shape is more popular and widely used compared to the conical shape because of the stability of the frustum shape in its upright position. Another difference between the frustum and conical shape is the presence of an outrigger at the bottom. The conical shape is mostly made with the diagonally woven/knotted bamboo strips overlaying the whole surface as shown in Fig-1(a). While the frustum shape has woven diagonal elements that bend at the bottom to form the outrigger system as shown in Fig-1(b). One of the most common elements between these two types of Doko is the circular belt made up of a hoop of about two centimetres in diameter. This belt is assumed to help in the distribution of load into the diagonal elements, and prevents the Doko from horizontal deflection as well as buckling under lateral load. Similarly, Dokos are commonly constructed either only using the diagonally woven/knotted elements or interlinking the diagonal members with the vertical columns like members as shown in Fig-2(a) or horizontal beam-like members as shown in Fig-2(b) or a combination of vertical and horizontal members as shown in Fig-1(b) and 2(c). Dokos of pure inclined members are generally used for carrying light goods whereas the latter types are used to carry heavier goods. In some Dokos, the horizontal members are either used at uniform spacing as shown in Fig-2(b), while in others it is only positioned near the base or near the mid-height, as shown in Fig-1(b). It is the understanding of the author that the inclined columns and beams like elements provide resistance to axial deformation and tensile failure of the diagonal elements resulting from the higher pulling/tensile force developed due to supported load. Moreover, the closely separated horizontal beam-like members used near the top and bottom is assumed to reduce the axial deformation at the base. Moreover, the diagonal elements are normally found to be present in both directions similar to cross bracing as shown in Fig-1(b). However, the diagonal elements running in only one direction as shown in Fig-2(b) can also be found in use. The angle of inclination of the diagonal elements to the horizontal direction is found to vary from as low as about 10 degrees as shown in Fig-2(a) to as high as 60 degrees as shown in Fig-2(b). The components of the Doko are shown in Fig-1.

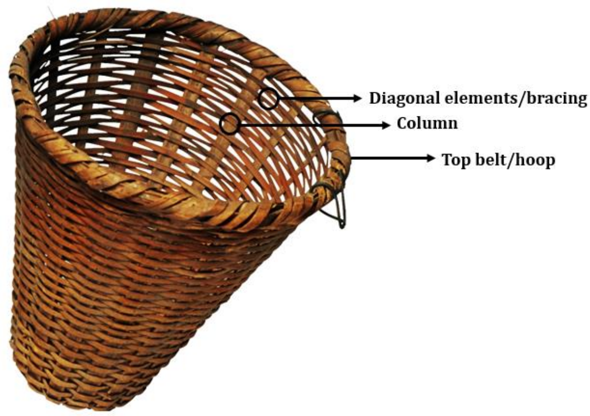


a. Conical Doko [3]



b. Frustum shaped inverted Doko [4]

Fig -1: Conical (a) and frustum shaped (b) Doko



a. Doko with diagonal members interlinked with the vertical columns like members

b. Inverted Doko with diagonal members interlinked with the horizontal beams like members [5]

c. Doko with diagonal members interlinked with columns and beams like members [6]

Fig -2: Different configuration of interlinking of diagonal members with beams and columns like members in Doko

The first objective of this study is to assess the structural features and mechanism of different configurations of Dokos and to select a suitable configuration that provides the most optimal building structural system. Different configurations of Dokos adopted into the DOKO system are discussed in Section 2. The second objective of this study is to compare the structural performance of the DOKO system and the conventional structural systems. This is achieved through lateral load analysis of eight building models (discussed in Section 2) consisting of eight different structural systems having the same floor plan and building dimensions. The detail of the case study buildings and the results of the computer analysis: maximum lateral and vertical displacements, shear force, axial loads, and bending moments are described in Section 4. In addition, possible economic, as well as environmental benefits and challenges of the DOKO system, are discussed in Section 5. From the analysis results, it is found that the DOKO structural system is highly efficient compared to the conventional system in providing strength and stability against lateral loads such as wind and earthquake.

2. Diagonally Operating Knotted Overlay (DOKO) Structural System

Diagonally operating knotted overlay or DOKO structural system proposed here has the outer diamond-shaped structural skeleton near the facade of the building and the extension of the diamond-shaped skeleton up to the centre of the roof forming an outrigger system similar to the Doko/basket discussed in Section 1. The configuration is similar to a hollow frustum with one end open and the remaining surface consisting of repeated diamond-shaped members. In contrast to Dokos, the building with the DOKO system stands with an opening at the base similar to Fig-3. This means the top hoop belt of Doko will work as the bottom hoop belt in the proposed DOKO system, and vice versa.

Similar to Doko, the diagonal elements, and top hoop belt is part of the fundamental DOKO system. However, the beams, columns, and bottom hoop belt may be considered optional. Moreover, the DOKO system can be designed as an individual system to carry all the lateral load or to take the major portion of the lateral load when mixed with other systems such as centrally located core walls. The floor system in the pure DOKO system can have building floors supported through pair of (internal and external) DOKO systems or supported through tension members such as ropes or cables. Moreover, in the combined system, the slab can be a completely flat slab system or consist of beams that are connected to the central core wall and the external DOKO system. Various components of the DOKO system are described below.

2.1 Diagonally knotted members

Diagonally knotted members are the fundamental structural elements in the DOKO system. It forms the external bracing unit of the diamond shape as shown in Fig-3. Though the configuration of these diagonal elements looks similar to the rotating frame (beam-column configuration) by about 10 to 70-degrees angle, the structural response of these two systems differ significantly. In the system with diagonal elements, the developed shear and overturning moment due to lateral load is resisted by axial action whereas in conventional frame system, it is resisted by bending action. The axial force induced by the lateral and gravity loads in the diagonal members takes a helical load path around the perimeter moving towards the base allowing long spans between each module. The diamond configuration also provides multiple load paths and offers redundancy during structural failure. The redundancy is also useful when undertaking repair or retrofit of the building. Moreover, compared to the more central positioning of the conventional core wall system, the positioning of the DOKO system at the building exterior

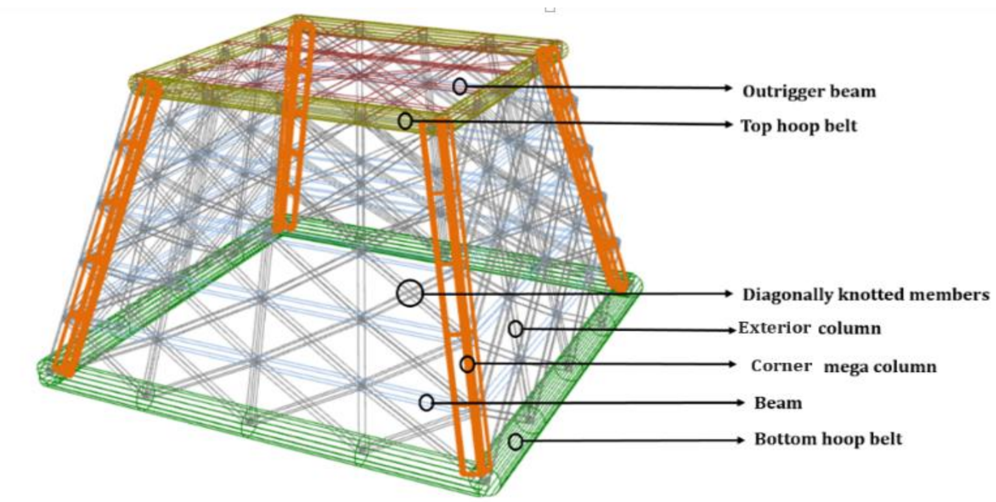


Fig -3: Trapezoidal prism shaped building showing components of DOKO structural system maximizes the overall building functionality as well as the torsional resistance of the building [7]. Similarly, these integrated elements also offer large column-free, vibrant and light reach internal space. Moreover, the past studies have concluded that the application of exterior bracing to building structural systems not only enhances structural performance and artistic effects but also reduces building materials and overall construction cost, improves post-earthquake recoverability, and overall sustainability [8-10]. Furthermore, these diagonal members can be designed in various sizes and angles to meet any desired building shape and functionality. The knotted or fully joined connection of these elements at the node or point of intersection can be created either at each floor level or at an interval of any desired floor levels. Based on the floor height, building aspect ratio, and the number of floors to be supported by each module, the angle of the diagonal elements with horizontal can vary from 10 degrees to 70 degrees (also observed in most of the Dokos in Fig-1 and 2). However, the past studies on external bracing have suggested using 60-70 degrees as the most optimal angle resulting in minimum overall lateral deflection and amount/weight of the material, and higher constructability [11-12]. Moreover, to optimize the design, the size of the diagonal members can be chosen based on the load path and the magnitude of the ultimate load. For example larger sizes near the base and smaller sizes near the roof. Similarly, using modular and composite materials such as steel, concrete-filled steel tube, precast concrete, and timber instead of in situ concrete can improve constructability.

2.2 Knotted joints

The joints between the diagonal elements and between each diagonal element and beam or column are considered valuable in the transfer of shear force, improving lateral stability, and improving the constructability of the DOKO system. The joint can be achieved either by the inherent knitting of one member over another or through mechanical joints. As the analysis or construction of inherently knitted joints has never been performed, it is only presented here as a possibility. With the advancement in prefabricated techniques and tensioning of large sections, the construction of inherent joints can be a possibility in the near future. Whereas, the construction of mechanical joints such as bolted or welded steel connections, and a connection of precast concrete has already been achieved for structures with extensive external bracing. The 'knotted' terminology used in the DOKO system represents both types of connection/joints presented above.

2.3 Diagonal outrigger beam

The deep diagonal outrigger beam at the roof of the building provides coupling action between the diagonally knotted members or columns that are under tension and the opposite members that are in compression, hence forming restoring moment and a strong lateral load resisting systems. This mechanism also contributes to reducing the tension and uplift forces in the diagonal members and columns. The functioning of these outrigger beams can be improved by providing an interior DOKO system or central core wall. Moreover, with the installation of the viscous damper, these beams can provide a significant amount of wind and seismic energy dissipation. The flexibility of construction of the deeper beam at the top of the building can be a significant benefit as these beams can provide considerable lateral stiffness compared to numerous weak beams at multiple levels. However, when needed for example in a tall building, multiple stronger outriggers can be provided in the DOKO system.

2.4 Beams and columns

Though the addition of the external beams or columns may create challenges with the fabrication or establishment of the DOKO system and may restrict the architectural requirement such as lighting and ventilation, these beams and columns can play a vital role in designing super high-rise buildings/structures that tend to fail due to excessive shortening or elongation of the diagonal elements. The perimeter beam can create a belt truss or indirect outrigger and contribute to enhancing the stiffness of the system, transmitting the vertical load and reducing the vertical deformation of the diagonal elements. Similarly, the perimeter columns and corner mega-columns as shown in Fig-3 can assist in transferring the gravity load and reducing the vertical deformation in the diagonal elements. Moreover, in the previous study, the author observed the positive contribution of corner mega columns or shear walls in increasing torsional resistance in the building [2]. Furthermore, these columns are also very important in creating an effective outrigger system as discussed in Section 2.3.

2.5 Top hoop belt

The top hoop belt has several functions including contribution to improving the lateral restrain of the system by forming a belt truss or indirect outrigger system, distribution and balancing of the load and reducing differential shortening of the diagonal elements, providing extra stiffness to the joint between diagonal elements and top outrigger beams, and providing continuous rigid support to the roof and façade elements at the top of the building.

2.6 Bottom hoop belt

Similar to the function of the top hoop belt, the bottom hoop belt contributes to the distribution of the forces at the base of the building. Moreover, it helps in effectively transferring loads to the ground, optimizing the design and construction of the foundation, and in facilitating a platform for base isolation if required.

2.7 Floor slab

The DOKO system can be used with any type of floor system. Generally, if the conventional cast in place slab is to be used, the perimeter beams need to be provided in the DOKO system. If the floor is to be constructed without using any internal core walls or columns, then an innovative floor system called here as suspended floors can be used instead of supported floors. In the suspended system, two ends of the slab are supported to the beam or diagonal members and the mid-span of the slab is connected to the elements of the DOKO system that are at the higher storey using cables as shown in Fig-4. This system is similar to the suspended deck of the suspension bridge. Moreover, flat RC void concrete slabs and composite slabs can be used to increase the span of the simply supported slabs.

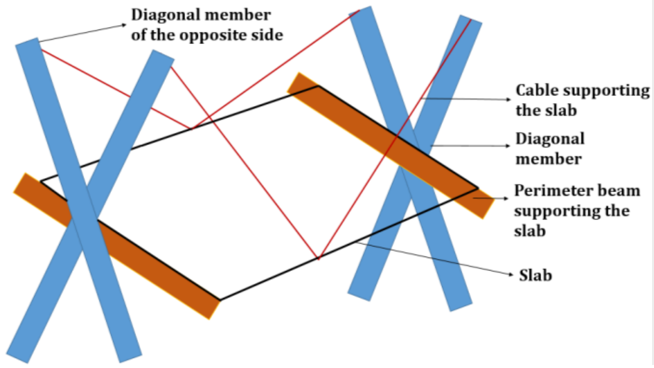


Fig- 4: Suspended floor system

2.8 Building façade

DOKO structural system allows the use of both traditional as well as flexible skin facades. The traditional façade can be provided either inside or outside or within the diagonal members of the DOKO system without the need for vertical or horizontal members in the façade panels. Moreover, a frameless flexible and completely overlaying skin façade that covers the whole surface of the building can also be built by supporting the façade through various elements of the DOKO system as shown in Fig-3. Transparent solar plastic or glass or other innovative façade materials can be used as a material for manufacturing the frameless skin facade. This skin façade can be installed easily using the crane or drone and then arranging and fixing/stapling can be done manually.

3. Double DOKO or Combined DOKO and Core Wall System

The single exterior DOKO structural system may only have the capacity to support the overall gravity load of the building with a smaller plan area and lower height. For a building with a larger plan area and height, either double (interior and exterior) or multiple DOKO systems or a combination of DOKO and core wall system as shown in Fig-5 may be considered. The combination of multiple DOKO systems or dual systems can contribute to controlling the amount of gravity load in the diagonal members as well as in increasing the lateral force resistance of the building. If a central core wall is provided, it may also increase the overall ductility of the system.

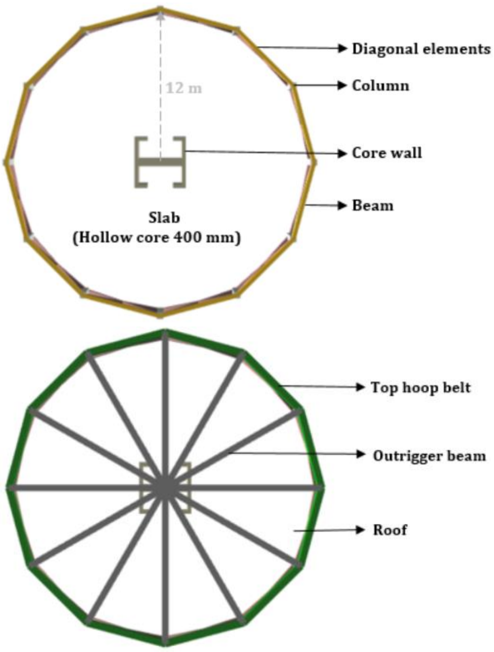


Fig -5: Floor plan of the typical floor (top) and roof (bottom) of the case study building

4. Comparison of Structural Performance of DOKO and other Conventional System

A case study building with a dodecagon or 12 sided polygon-shaped floor plan having a radius of 12 m is selected to compare the structural performance of DOKO and conventional structural systems. Though the DOKO system is proposed here for all ranges of height including super highrise buildings, for the sake of simplification, a low-rise building of four-storey with twelve meters in height was selected in this study. Eight different versions of this particular building consisting of eight different structural systems as listed below were then modelled in reputed computer software SPACE GASS [13].

- System 1: Pure moment resisting frame (MRF)
- System 2: Pure shear wall
- System 3: MRF and shear wall
- System 4: Fundamental (no beam and column) DOKO system

- System 5: DOKO system with beams
- System 6: DOKO system with columns
- System 7: DOKO system with beams and columns
- System 8: DOKO and core wall system

The details of the floor plan and the structural layout for the case of 'System 8' is shown in Fig-5. Likewise, the elevation view of the building and the structural element sizes are shown in Fig-6 and Fig-7, respectively. As the floor plan for the other systems listed above are same, the floor plan for these systems are not provided. Similarly, the structural layout of other systems can be derived from Fig-5 by removing certain elements. For example, 'System 1' will have only the beam and columns, while 'System 7' have all the elements except the core wall.

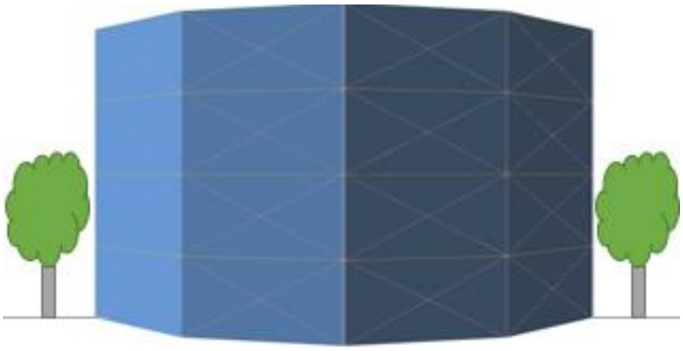


Fig- 6: Elevation view of the building with DOKO system

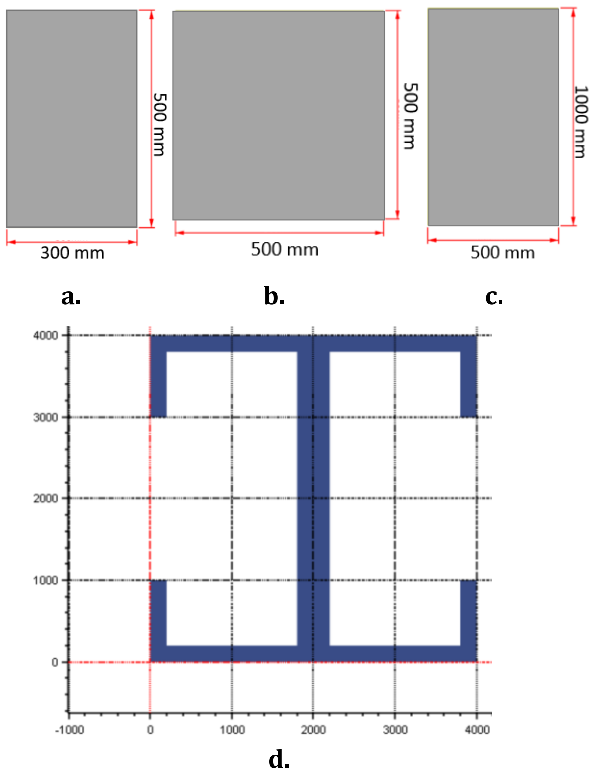


Fig- 7: Sizes of the beams and diagonal elements (a), columns (b), top belt and outrigger (c), and core wall (d).

Flexible joints between the diagonal elements were modelled to simulate the knotted or woven joints. However, a near rigid connection can be modelled if cast in situ or other physical connection to be used. Regarding the material properties, 40 MPa standard grade of concrete was used. Moreover, to simulate the real serviceability load and seismic mass of the building, floor lives load rating of 2.5 kPa, and the superimposed load of 0.5 kPa were used in addition to the self-weight of the building. Furthermore, to simulate the real lateral load, a lateral load profile equivalent to seismic forces due to a response spectral acceleration of 0.54'g was used. The load profile is shown in Fig-8.

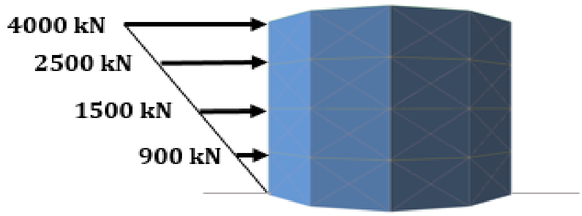


Fig- 8: Lateral load profile used for the analysis

The maximum lateral deflection ($\Delta_{max,x}$), maximum vertical serviceability deflection ($\Delta_{max,y}$), maximum shear force or axial force (V_{max}), and maximum bending moment (M_{max}) in different structural elements of the eight structural systems obtained from the SPACE GASS analysis are presented in Table 1.

Table-1: Maximum lateral and vertical deflection, shear or axial force, and bending moment in different structural elements of the eight structural systems.

Structural systems	$\Delta_{max,x}$ (mm)	$\Delta_{max,y}$ (mm)	**V_{max} (kN)**	**M_{max} (kNm)**
System 1	183	1.80^{D}	811^{C}	1870^{C}
System 2	12.48	1.50^{D}	8900^{W}	82200^{W}
System 3	11.56	1.00^{D}	8723^{W}	77562^{W}
System 4	9.14	43.80^{D}	1368^{D}	40^{D}
System 5	9.14	45.00^{D}	1368^{D}	35^{D}
System 6	4.28	7.00^{D}	774^{D}	16^{D}
System 7	4.24	7.00^{D}	770^{D}	12^{D}
System 8	2.75	0.83^{D}	231^{D}, 6407^{W}	5^{D}, 29846^{W}

***C = column, W = wall, and D: diagonal element of DOKO**

From Table 1, it is shown that the structural performance of the building with a pure moment resisting frame (MRF) system (System 1) is considered poor compared to other structural systems. In the MRF system, the lateral deflection which is 183 mm for the considered earthquake load is significantly higher than the general limit of 'height/500'or 24 mm. The lateral deflection in all other systems is found within this limit. Similarly, the combined external MRF and core wall (System 3) is found to have similar lateral deflection results compared to the pure shear wall or core wall system (System 2). A similar effect was found for the case of shear and moment. Therefore, introducing an external MRF to the core wall system may not be beneficial as expected. From the design point of view, the pure DOKO system with the column but without the beam (System 6) is found to have the most optimal solution. It can be inferred from the table that introducing 'System 6' in the building contributed to design forces and moments within the reasonable range and also in reducing the maximum lateral deflection by one third compared to the combined MRF and wall system (System 3). Though the addition of beam to 'System 6' resulting in 'System 7' only resulted in a small reduction in the design actions and maximum lateral deflection, these beams may be required for adopting flat slab construction. Moreover, when comparing the DOKO system with different structural configurations, it is found that the fundamental system without beam and column (System 4) may only be used in low-rise structures due to possible larger vertical displacement in the diagonal elements resulting in higher axial shortening and damages of these elements. Considering the axial deformation of diagonal elements, for mid-rise structure, 'System 7' is recommended and for high-rise and super-high-rise structures combination of two or more DOKO or DOKO and core wall system similar to 'System 8' is recommended. Furthermore, on combining DOKO and core wall system, it is found that the maximum lateral deflection is reduced by more than 75% and the bending moment in the wall is reduced by more than 60% compared to the combined shear wall and moment-resisting frame (System 3). Therefore, from the above comparison, the DOKO system is found to have considerably higher structural performance compared to conventional systems (System 1-3).

5. Opportunities and Challenges

The structural robustness against lateral loads as discussed in Section 4 combined with other possible technical benefits such as the creation of column-less space and having a multiple load path which provides structural redundancy, material and cost efficiency achieved as a result of complete or partial omission of the core wall and suitability to modular and automated construction technique without the need for external scaffolding, and suitability to energy-efficient building envelope makes the DOKO system technically, materially, economically, and environmentally sustainable. Moreover, its applicability to building with all ranges of size and heights including super-tall buildings, building with smaller plan areas, buildings that required quick construction, building with flexible skin façade, and tilted or rotated buildings makes it an advanced structural system to support and bring innovation in the infrastructure industry. Despite having the above benefits, there can be several challenges in the application of the DOKO system such as design analysis and construction-related challenges, limitation in the creation of large external openings at the ground floor, issues with construction and fabrication of nodes/joints and diagonal elements, and lack of local expertise for the construction. The author proposes further research for a more comprehensive study of these issues.

6. Conclusions

The objective of this study is to introduce an innovative structural system known as a 'diagonally operating knotted overlay (DOKO)' structural system that resembles the Doko (a bamboo basket). In this regard, the structural performance and application of the DOKO structural system to buildings were studied by assessing its response to gravity and lateral load and comparing it to the responses of the conventional systems: moment-resisting frame, shear wall, and combined system. Based on the comparison, the DOKO system is found to perform considerably better than the conventional system. Furthermore, the following conclusions about the DOKO system are made:

- The fundamental DOKO system (without beam and column) are found to reduce the maximum lateral deflection by more than 20 times compared to the same building with a pure moment resisting frame (MRF). Similarly, the fundamental DOKO system is found to perform better than the dual system (wall and MRF). However, due to the considerably higher vertical deflection under serviceability conditions, the fundamental DOKO system may be limited to use in low-rise structures.
- The DOKO system with columns but without beams is found to provide the most optimal solution: higher strength but lesser material. This system reduced the maximum lateral deflection by three times compared to the combined MRF and wall system and more than 40 times compared to the pure MRF system. Though the full DOKO system (with both beam and column) is found to perform similar to the system without beam, a full system may be preferred when adopting flat slab construction that requires side beams to support slabs and to maintain the floor rigidity.
- A full DOKO system (System 7) is recommended for mid-rise structures, while a combination of two or more DOKO or DOKO and core wall systems is

recommended for tall and super tall buildings. On combining the system, the bending moment in the wall was reduced by more than 60% compared to the combined shear wall and MRF system.

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BIOGRAPHY

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