Centre for Urban Greenery & Ecology
CUGE Standards

GUIDELINES ON **DESIGN LOADS FOR SKYRISE GREENERY**

CS E10:2014

Guidelines on Skyrise Greenery

CS E: Skyrise Greenery
CUGE STANDARDS CS E10:2014

GUIDELINES ON
DESIGN LOADS FOR SKYRISE GREENERY

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CS B Landscape construction and management
CS C Urban ecology
CS D Landscape design
CS E Skyrise greenery

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Design Loads for Skyrise Greenery

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The CUGE Standards will be reviewed every three years. Concurrently, CUGE also gathers new information continually through on-going research.

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Design Loads for Rooftop Greenery

SECTION 1 SCOPE

1.1 INTRODUCTION

These guidelines set out the basic requirements and considerations for design loads in the design, planning and construction of rooftop and vertical greenery.

Rooftop and vertical greenery are urban solutions to introduce vegetation onto man-made surfaces, such as the concrete roof and façade envelope of buildings, which have been designed, engineered and built with predetermined load-bearing capacities and limitations. Therefore, unlike ground level landscaping, the design and construction of rooftop and vertical greenery is often biased towards lightweight greenery systems and strategies.

In the design, planning and engineering of rooftop and vertical greenery, when estimating expected design loads, it is important to base the estimations on the saturated weight of the selected greenery systems and the matured weight of the plants (This applies to rooftop trees/palms and tall shrubs.)

1.2 OBJECTIVE

This is a guide to estimate loads on rooftop and vertical greenery.

The design and construction of rooftop and vertical greenery shall comply with the relevant codes of practice and standards of the relevant authorities.

1.3 DEFINITIONS

Green roof

Extensive green roofs are generally not designed for active recreational use. They are developed mainly for aesthetic and ecological benefits. Generally, they are low in installation cost, lightweight (90-150 kg/m^2), with shallow mineral substrates and minimal maintenance required. Inspection should be performed, at the minimum, once or twice a year. Plants selected are usually of low maintenance and are self-generative. Extensive systems are common in European countries, especially Germany and increasingly being installed in North America cities as well. Generally, they can also be placed on pitched roofs of up to an inclination of 30 degrees.

Roof garden

Intensive green roofs, or roof gardens, are designed to be accessible. They are often used for recreation and other social activities. Hence they are associated with added weight, higher capital cost, more intensive planting and higher maintenance requirements. The plant selection ranges from ornamental lawn, shrubs, and bushes to trees and palms. As they are designed for usage, regular maintenance such as mowing, fertilizing, watering and weeding is required.

Vertical greenery (Green wall)

Vegetated walls are built mainly for aesthetic and ecological benefits. The level of maintenance is often dependent on the design and safe accessibility of these vegetated vertical surfaces. Vertical vegetated wall surfaces are often comparatively more exposed to the drying effects of wind, especially with stronger wind at increase altitude. Growing plants in such harsh environment does require more care and frequent inspection of the plants and systems. The plant selection ranges from ornamental ground-covers, shrubs, to climbing vines and cascading plants. These are usually designed for visual appreciation. Regular maintenance such as fertilizing, irrigation and judicious pruning (if the vegetated surfaces are safely accessible) are required on a regular basis. There are various methods of planting on vertical surfaces, with cost getting competitive and more affordable in recent years.

Rooftop greenery

Is the collective term for green roof (for both flat and pitched types) and roof garden (including ledge greening).

Skyrise greenery

Is the collective term for rooftop greenery and vertical greenery.

1.4 PERFORMANCE REQUIREMENT

1.4.1 During design, planning and construction of skyrise greenery, the expected combined loads (which include the dead loads, live loads, human loads, wind loads, imposed loads and any other intended loads) must be accommodated and safely transferred through the load-bearing structures to the building foundations and to the ground, without impairing the structural stability and integrity as intended and endorsed by the registered Professional Engineer (PE).

1.4.2 For rooftop greenery, the underlayments such as the waterproofing, thermal-insulation and root-penetration barriers must be detailed with adequate compressive and tensional strength. Point loads, if any, must not compromise these functional layers.

1.4.3 It is important that owners, tenants, operators and building management are informed about the roof and wall loading limits and other restrictions, if any. This is to avoid future inappropriate relocation and/or addition of plants and greenery systems onto surfaces and areas not designed to accommodate the additional weight.

1.4.4 When retrofitting greenery systems onto existing roof and wall surfaces, registered PE must be consulted. Any engineering solutions developed must be endorsed by the registered PE. Should the existing roof and/or wall be structurally inadequate, new supports as engineered by the registered PE will be required for safe effective load transfer of the newly fitted greenery systems.

1.5 GENERATE LOAD MAP OF ROOFTOP/VERTICAL GREENERY

1.5.1 Depending on design, the load distribution across a roof and/or wall surface, involving loads from vegetation and greenery systems (and other associated loads, such as superimposed and equipment loads during periodic maintenance, etc.), can be complex, especially when it involves unpredictable site forces, such as storm wind load, etc.

1.5.2 Once the design team (which include the architect, registered PE, landscape architect and any other relevant professional) formulated the initial architecture concept and design, the appointed registered PE will have to determine and generate load maps/estimations to clearly illustrate the expected dead loads, live loads and their distribution, based upon assumptions made on the communicated design/data and expected usage.

1.5.3 Registered PE must use current wind engineering practices consistent with BS 6399: Part 2 or BS EN 1991-1-4 and the design should be approved by the relevant building authority having jurisdiction.

1.5.4 Associated performance specifications and expectations can be cross-referenced to the generated load map, to clearly illustrate the design criteria for the roof/wall construction and engineering, facilitating discussions amongst stakeholders on project-bidding processes.

1.5.5 On the load map, areas set aside for rooftop tree/palm, sloped green roof and area with deeper/heavier substrate layers will require more attention.

1.6 FACTORS INFLUENCING LOADS OF ROOFTOP GREENERY

<table>
<tr><th colspan="2" rowspan="2">Factors contributing to the loads on rooftop greenery:</th><th colspan="2">Loading Advice</th></tr>
<tr><th>(for new building)</th><th>(for existing building)</th></tr>
<tr><td>1</td><td>Depth and volume of growth-media</td><td>➢ Appropriate use of lightweight soil alternatives (commonly used in lightweight green roof systems) for suitable shrub plants can be a strategy to reduce loads.</td><td>➢ Registered PE to check the existing roof load bearing capacity.
➢ Registered PE, registered architect and green roof consultants to ascertain rooftop greenery design.</td></tr>
<tr><td rowspan="2">2</td><td rowspan="2">Slope of green roof</td><td>➢ Generally, the steeper the roof-pitch, the greater the expected shear forces within the green roof system.</td><td>➢ Ascertain existing roof slope angle. Select suitable green roof system.
➢ Green roof design must address expected loads (i.e. wind uplift, shear forces, loads during maintenance).</td></tr>
<tr><td colspan="2">➢ Please refer to CS E08, Guidelines on design and construction of pitched green roof.</td></tr>
<tr><td rowspan="3">3</td><td rowspan="3">Rooftop tree / palm / tall shrubs</td><td>➢ Trees (more than 8m height) will need larger soil volume for rooting. The saturated weight of large soil volumes can add substantial load to the roof.</td><td rowspan="2">➢ Existing roof's load bearing capacity has to be ascertained, reinforced and engineered by registered PE.</td></tr>
<tr><td>➢ Small trees (3 to 6m height) are preferred.</td></tr>
<tr><td colspan="2">➢ Please refer to CS E09, Guidelines on planting of trees, palms and tall shrubs on rooftop.</td></tr>
<tr><td>4</td><td>Roof garden features/structures (i.e. landscape rocks, water features, pavilions, etc.)</td><td>➢ Rooftop features with higher loads should be positioned over load-bearing columns and beams for effective load transfer. This applies to:
(1) Large feature rocks and/or rock piles
(2) Large water bodies
(3) Sheltering structures (ex: pavilion)</td><td>➢ Existing roof's load bearing capacity has to be ascertained, reinforced and engineered by registered PE.</td></tr>
</table>

5	Water storage capacity of the rooftop greenery	➢ Some rooftop greenerysystems are capable of more water storage. While benefitting the plants, this increases load across the roof surface. ➢ Rainwater harvesting system, must be engineered within the building's loading limitations.	➢ Saturated load of selected rooftop greenery system must be considered. ➢ Rainwater harvesting system, when retrofitted onto existing building, must be engineered within the building's loading limitations.
6	Public accessibility of the rooftop greenery	➢ Ascertain live loads of rooftop greenery during the design and planning phase.	➢ For retrofitted works, involving conversion of inaccessible roof surface into accessible, usable roof space; (1) Registered PE must be consulted; (2) Additional load-bearing structures and/or structural reinforcement may be necessary, as advised by Registered PE.
7	Vehicular accessibility of the rooftop greenery	➢ Ascertain vehicular loads on roof (i.e. riding lawn mower, etc.) during the design and planning phase.	➢ Existing roof's load bearing capacity has to be ascertained, reinforced and engineered by registered PE.
8	Water ponding on rooftop greenery resulting from inadequate and/or ineffective drainage	➢ Provide adequate drainage outlets, detailed to effectively drain excess water and prevent storm water built up.	➢ Retrofitted rooftop greenery must be detailed to provide adequate drainage outlets, detailed to effectively drain excess water and prevent storm water built up.

SECTION 2 LOADING CONDITIONS OF SKYRISE GREENERY

<table>
<tr><th colspan="5">Rooftop greenery loads</th></tr>
<tr><td rowspan="5">Dead loads</td><td rowspan="5">Material loads</td><td rowspan="2">Substrate load</td><td>Substrate depths</td><td>Table 1</td></tr>
<tr><td>Substrate material weights</td><td>Table 2</td></tr>
<tr><td rowspan="2">Vegetation load</td><td>Turf / Shrub weights</td><td>Table 3</td></tr>
<tr><td>Tree / Palm weights</td><td>CS E09:2012</td></tr>
<tr><td>Support system load</td><td>Common material weights</td><td>Table 4</td></tr>
<tr><td rowspan="4">Live loads</td><td>Maintenance equipment loads</td><td colspan="2">Equipment loads (maintenance)</td><td>Table 5</td></tr>
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<tr><td colspan="2">Wind loads on vertical greenery</td><td>Section 3.3</td></tr>
</table>

2.1 FUTURE LOAD ALLOWANCE FOR SUBSTRATE (GROWTH MEDIA)

2.1.1 The growth media for rooftop greenery comes in a variety of mixtures. (Please refer to Table 2 for examples) As the volume of growth media may settle over time, it is common practice to add more growth media periodically, as required. To account for these future additions of growth media and inconsistencies in grading, the specified depth of the saturated growth media should be increased by no less than 15% for the purpose of structural load calculations.

2.1.2 However, do not use the future load allowances in calculations when the load of the growth media is intended to counteract any uplift or overturning forces (such as that by the wind).

2.2 DEAD LOADS

2.2.1 Dead load, in Civil Engineering, is the intrinsic invariable weight of a structure, such as that of a building. It may include any permanent loads attached to the structure. Superimposed Dead load (SDL) refers to finishes, services and would include the weight of a green roof.

2.2.2 For roof garden dead load, part of the SDL, consists of the expected grown-weight of rooftop trees/palms and the saturated weight of the soil volumes within the planters.

2.2.3 Saturated soil/substrate weight should be calculated as dead loads. Planters are usually auto-irrigated, with the intention of ensuring the soil/substrate volume remains moist throughout the day.

2.2.4 Saturated loads of rooftop greenery systems

- For rooftop trees/palms, the suggested soil/substrate volume and associated saturated load, can be estimated as recommended in *CS E09:2012, Guidelines on planting of trees, palms and tall shrubs on rooftop*.
- For convenience of calculation, soil saturated weight is estimated at 1920 kg/m^3 (120 lb/ft^3). For the recommended soil depths of various vegetation types, please refer to Table 1.
- Saturated load of the under-layers that may function as the integrated reservoir of the rooftop greenery system.
- In the worst case scenario, roof drains can be clogged and the roof is drained through the overflow downpipe(s). Roof loading should always be designed for such foreseeable conditions and include the associated loading for water level as high as the overflow downpipe(s).

2.2.5 Minimum dry weight of soil/substrate volume of extensive green roof

- The minimum dry weight of the soil/substrate volume of the lightweight extensive green roof should ideally be not less than 49kg/m^2. Please refer to Table 6.
- System lighter than 49kg/m^2 will need to be adhered and/or mechanically attached to the roof surface to resist the registered PE estimated wind uplift force.

2.2.6 Saturated loads of vertical greenery systems

- Saturated load of the substrate media.
- Should the vertical greenery system consist of an integrated water retentive layer, the saturated load must be included.

2.2.7 Loads from plants

- Estimated load of various forms of vegetation are as suggested in Table 3.
- Wherever possible, get estimates of the tree/palm loads directly from the local nurseries.
- Load of trees/palms can be estimated as recommended in *CS E09:2012, Guidelines on planting of trees, palms and tall shrubs on rooftop*.
- Tree point load should be concentrated over the projected horizontal area of the tree planter pit. The tree point load should be based on the expected grown green weight of the tree.

- Should there be green roof systematic layers installed beneath the tree, the load bearing capacity of these layers must be verified with its provider using the expected grown green weight estimates of the tree.

2.2.8 Loads of rooftop maintenance equipment

- Load of equipment used during the maintenance of rooftop greenery and vertical greenery.
- Examples of such equipment are the riding mower, lightweight MEWP, tower scaffold, etc. Such equipment may track across the rooftop surface during maintenance, contributing to the loading on the roof structures.
- For estimated loadings of such equipment, please refer to Table 5.

2.2.9 Loads of rooftop structures and finishes

- Load of landscape features (i.e. pavilions, water features, green walls, planters, etc.)
- Load of hard-scape materials used on the roof garden/green roof, such as stone slabs, timber decking and other surface finishes (i.e. screeds, waterproof membranes, insulation etc)
- For estimates on the density of common materials used in the construction of rooftop greenery and vertical greenery, please refer to Tables 1, 2, 3 and 4.

2.2.10 Please refer to the following:

- Schedule of Weights of Building Materials – BS 648
- Loading for Buildings. Code of Practice for Dead and Imposed Loads - BS 6399: Part 1
- Actions on structures. General actions – Densities, self-weight and imposed loads for buildings - SS EN 1991-1-1

2.2.11 Please note that:

- With effect from 1 April 2015, the SS and BS will be withdrawn from the BCA Approved Document and the SS ENs will be the only prescribed design standards.

2.3 LIVE LOADS

2.3.1 Live load is the load produced by the use and occupancy of the building structure. It is the moving, variable weight added to the dead load or intrinsic weight of a structure. This also includes all unfixed items such as unanchored furniture. For rooftop greenery, the expected human loads from users and during maintenance are considered live loads.

2.3.2 Imposed live load for extensive green roof:

- Extensive green roof is usually designed as a thermal buffer, as an aesthetic vegetated rooftop surface and is usually non-accessible.
- Such extensive green roof, accessible only during maintenance, should be designed and engineered with its associated loading during maintenance (and their associated heavy maintenance equipment – although permanently fixed rails, tracks and cranes would be considered SDL).
- Such loading considerations must be addressed during the planning and design phase.
- The occupant live load imposed for flat roof - accessed for maintenance only – shall be with compliance to the Building Control Regulations, Cap. 29, Rg 26, 27 and the fifth schedule. However this should be reviewed if it is anticipated that the flat roof may be used for public assembly, e.g. amphitheatre.

2.3.3 Imposed live load for intensive roof garden:

- Intensive roof garden is designed for recreational purposes. Occupancy load of intensive roof garden is dependent on the function of the rooftop space.
- Registered PE to ascertain the expected live loads based on the intended function of the roof.
- Publicly accessible intensive roof garden should be designed and engineered with its associated loading during maintenance (and their associated heavy maintenance equipment – although permanently fixed rails, tracks and cranes would be considered SDL)
- Such loading considerations must be addressed during the design and planning phase.
- For super high-rise residential buildings, roof gardens may be designed to double up as holding area at the refuge floors during fire emergency. The associated human traffic loads during such times of emergency must be considered during design phase.

2.3.4 Anchor points (and safety lines, etc.) for fall-prevention systems (i.e. fall-restraint system, fall-arrest system, etc.) must be designed, engineered and installed to the required loading capacity as advised by Workplace Safety and Health (WSH) Council and Ministry of Manpower (MOM) Singapore. Please refer to:

- *Workplace Safety and Health Guidelines – Anchorage, Lifelines and Temporary Edge Protection Systems*
- *CS E11:2014, Guidelines on Design for Safety of Skyrise Greenery*

2.3.5 For imposed roof and wind loads estimations, please refer to:

- Loading for Buildings. Code of Practice for Wind Loads – BS 6399: Part 2
- Loading for Buildings. Code of Practice for Imposed Roof Loads – BS 6399: Part 3
- Actions on structures. General actions - Wind actions – SS EN 1991-1-4
- Actions on structures. General actions – Densities, self-weight, imposed loads for buildings – SS EN 1991-1-1

2.3.6 Users of accessible rooftop greenery spaces consist of the visitors to the roof garden as well as the maintenance workers. Most vertical greenery surfaces are non-accessible. However some are designed with maintenance corridors. Skyrise greenery must be appropriately designed, engineered and installed to accommodate all expected human loads.

2.3.7 Equipment and machines may be deployed for skyrise greenery maintenance. Should heavy equipment be involved (i.e. MEWP, heavy riding mower to lawn a turf roof, etc.), the loads of such heavy equipment during operation must be accommodated in the design of the roof's load-bearing structure. Wherever possible, design to avoid the need for heavy maintenance equipment on the skyrise greenery. Ideally, design the skyrise greenery, with suitable plant selection, to allow maintenance using simple manual tools.

2.3.8 Please refer to Table 5 for some estimates on loads associated with human and maintenance activities.

2.4 ADDITION & ALTERATION (A/A) WORKS TO EXISTING BUILDING SURFACE

2.4.1 Loading issue is of major concern in A/A works.

2.4.2 Although there are many lightweight green roof systems and green wall systems available, it is very important to get a registered PE to ascertain the loading capacity of the existing structures and surfaces.

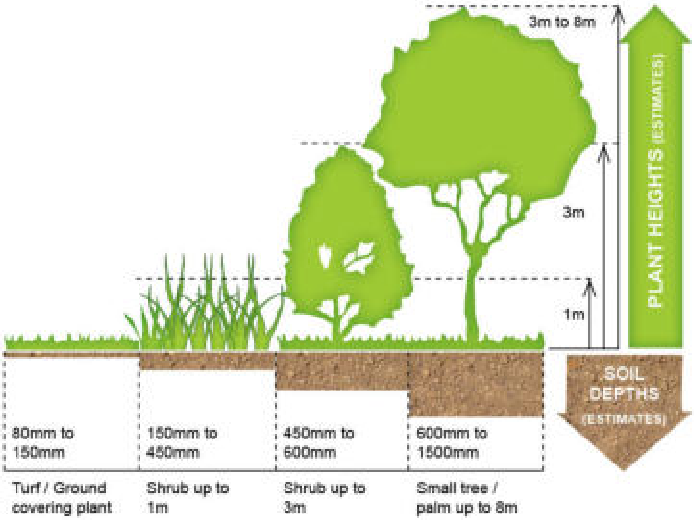
2.4.3 Often the existing building load-bearing structures and surfaces will need reinforcements to accommodate the new loads.

2.4.4 Should the A/A works involve installing a lightweight green roof system over an existing metal roof, the registered PE has to first inspect the existing roof for any structural risk. Poor quality metal roof must be replaced. It is important to note that future inspection of the metal roof for rust and corrosion will not be easy to carry out.

2.4.5 For A/A works involving installing vertical greenery onto an existing building façade, wherever possible, design the new addition with direct load transfer to the building foundation and/or to the ground. The existing building façade, against which the new addition is built, will then only serve to structurally brace the new addition against lateral loads, such as that generated by wind.

2.5 TABLE 1

Recommended substrate/soil depths*



Vegetation types	Recommended substrate/soil depths*
Turf / herbaceous / sedum greening (on green roof)	80 – 150mm
Wild grass-herbaceous greening (on green roof)	80 – 150mm
Turf / herbaceous / sedum greening (on green roof)	100 – 300mm
Wild grass-herbaceous greening (on green roof)	100 – 300mm
Ground cover / Flowering small shrubs	150 – 300mm
Small shrubs over 150 cm and up to 1m height	300 – 450mm
Big shrub (up to 3m height) & hedging palms	Min. 0.6m
Small tree & palm (3 to 6m height)	0.8 – 1.0m
Medium size tree & palm (>6m height)	1.2 – 1.5m

*Excluding filter layer and drainage layer

Substrate Load – Substrate Dimensions

- **Soil depths** (range) for the various vegetations types are as suggested above.
- **Soil volume** recommendations for tree and palm are available in *CS E09:2012*, Guidelines on Planting of Trees, Palms and Tall Shrubs on Rooftop.
- For the shallower range of soil depths shown, plants known to tolerate shallow soils must be selected. Field trials in the shallow soil for at least six months are recommended to determine which plant species will survive in these minimal depths.

Please also refer to Section 2.4 (Rooftop soil quality) of *CS E09: 2012. Guidelines on Planting of Trees, Palms and Tall Shrubs on Rooftop.*

TABLE 2

Estimated load of soils and other green roof materials (per 100mm course depth)					
Material(substrate)	**kN/m²**	**kg/m²**	**Material(substrate)**	**kN/m²**	**kg/m²**
Top soil, loose dry	1.20	122	Vermiculite, expanded	0.27	27.2
Top soil, loose moist	1.23	125	Approved Soil Mix, dry	0.78 – 1.18	80 - 120
Clay, dry	1.57	160	Compost, dry	0.49 – 0.78	50 - 80
Clay, wet	1.73	176	LECA, dry	0.44 – 0.78	45 - 80
Gravel, dry	1.65	168	Pebbles	1.86	190
Gravel, wet	1.96	200	Crushed brick	0.98 – 1.28	100 - 130
Perlite, expanded	0.05	4.8	Water	0.98	100
Pumice	0.71	72.1			
Sand, dry	1.53	155.5			
Sand, wet	1.87	190.5			

Source: Adapted from http://www.engineeringtoolbox.com/dirt-mud-densities-d_1727.html (cross-ref from CS E09:2012)

Estimated load of substrate mixtures for green roofs and roof gardens					
	Load per 10cm (100mm) course depth		**Mean water storage per 10cm (100mm) course depth**		
Substrate Mixture (roof garden)	**kN/ m²**	**Kg/m²**	**l/m²**	**kN/m²**	**Kg/m²**
Soil/mineral material mixtures	1.60 – 1.90	163 – 194	30	0.29	30
Soil/foam* material mixtures	1.30 – 1.50	133 – 153	25	0.25	25
Soil/organic material mixtures	1.50 – 1.70	153 – 173	35	0.34	35
Peat/mineral material mixtures	1.10 – 1.20	112 – 122	75	0.74	75
Composts/mineral material mixtures	1.10 – 1.30	112 – 133	65	0.64	65
Substrate Mixture (green roof)	**kN/ m²**	**Kg/m²**	**l/m²**	**kN/m²**	**Kg/m²**
Lava mixtures	1.45 – 1.65	148 – 168	44	0.43	44
Lava/pumice mixtures	1.25 – 1.30	128 – 133	42	0.41	42
Lava/pumice/dolomite mixtures	1.45 – 1.65	148 – 168	39	0.38	39
Lava/pumice/tuff mixtures	1.45 – 1.65	148 – 168	47	0.46	47
Sand/lava mixtures	1.60 – 1.75	163 – 179	50	0.49	50
Expanded clay mixtures	1.00 – 1.30	102 – 133	49	0.48	49
Expanded slate mixtures	1.10 – 1.30	112 – 133	49	0.48	49
Mixtures of crushed brick chippings	1.30 – 1.60	133 – 163	39	0.38	39

*Foam herein refers to expanded polystyrene granules, perlite, vermiculite, etc.
Source: Adapted from the FLL Guidelines for the Planning, Construction and Maintenance of Green Roofing – Green Roofing Guidelines, Germany, 2008 English edition

Source: Adapted from http://www.engineeringtoolbox.com/dirt-mud-densified_1727.html (cross-ref from *CS E09:2012*)

TABLE 3

Estimated load of vegetation for green roofs and roof gardens		
Green roof	**kN/m²**	**kg/m²**
Turf / herbaceous / sedum greening	0.10 – 0.15	10.2 – 15.3
Wild grass-herbaceous greening	0.10 – 0.15	10.2 – 15.3
Shrubs over 150cm height	0.20	20.4
Roof garden (Turf/Shrubs)	**kN/m²**	**kg/m²**
Turf	0.10 – 0.15	10.2 – 15.3
Low shrubs / ground covers	0.10 – 0.15	10.2 – 15.3
Shrubs over 150cm and up to 1m height	0.20	20.4
Shrubs/Bushes up to 3m height	0.30	30.6
Source: Adapted from the FLL Guidelines for the Planning, Construction and Maintenance of Green Roofing – Green Roofing Guidelines, Germany, 2008 English edition		
Roof garden (rooftop tree / palm)		
For algorithms to estimate the (living) weight of rooftop trees and/or palms and the associated soil volumes required for healthy growth, please refer to *CS E09:2012, Guidelines on the Planting of Trees, Palms and Tall Shrubs on Rooftop.*		

TABLE 4 (density estimates of common materials used in skyrise greenery construction)

Material types		
Stone / Rock	**kg/m³**	**kN/m³**
Stone	2300 – 3000 [6]	22.6 – 29.4
Granite	2600 – 2800 [6]	25.5 – 27.5
Limestone	2700 – 2800 [6]	26.5 – 27.5
Sandstone	2100 – 2400 [6]	20.6 – 23.5
Concrete	**kg/m³**	**kN/m³**
Concrete (precast)	2100	20.6
Concrete (reinforced)	2400	23.5
Concrete, lightweight	450 – 1000 [5]	
Concrete, medium	1300 – 1700 [5]	12.8 – 16.7
Concrete, dense	2000 – 2400 [5]	19.6 – 23.5
Brick	1400 – 2400 [2]	13.7 – 23.5
Brickwork in cement	1794 [2]	17.6
Brickwork in mortar	1602 [2]	15.7
Timber	**kg/m³**	**kN/m³**
Hardwood timber		
Teak, India	650 – 900 [2]	6.37 – 8.83
Teak, Africa	980 [2]	9.61
Teak, Burma	740 [2]	7.26
Meranti, dark red	710 [2]	6.96
Mahogany, African	500 – 850 [2]	4.90 – 8.34
Mahogany, Cuban	660 [2]	6.47
Mahogany, Honduras	650 [2]	6.37
Mahogany, Spanish	850 [2]	8.34
Keruing	740 [2]	7.26
Iroko	660 [2]	6.47
Ash	650 – 850 [2]	6.37 – 8.34
Beech	700 – 900 [2]	6.86 – 8.83
Birch	670 [2]	6.57
Cherry	630 [2]	6.18
Walnut	570 – 700 [2]	5.59 – 6.86
Oak	600 – 900 [2]	5.88 – 8.83
Elm	550 – 820 [2]	5.39 – 8.04
Softwood timber		
Pine	350 - 670 [2]	3.43 – 6.57
Cedar	380 - 580 [2]	3.73 – 5.69
Spruce	400 - 700 [2]	3.92 – 6.86
Redwood	450 - 510 [2]	4.41 – 5.00
Cypress	510 [2]	5.00
Larch	500 - 550 [2]	4.90 – 5.39
Wood products / composites		
Bamboo	300 – 400 [2]	2.94 – 3.92
Wood cement board	600 [1]	5.88
Rubberwood (Malaysian oak)	595 (average dried weight) [4]	5.84

Palm wood (coconut wood)	High density (dermal)	600 -900 [3]	5.88 – 8.83
	Medium density (sub-dermal)	400 – 600 [3]	3.92 – 5.88
	Low density (core)	200 – 400 [3]	1.96 – 3.92
Metal or Alloy	**kg/m^3**		**kN/m^3**
Aluminum	2712		26.60
Aluminum - 1100	2720		26.67
Aluminum - 6061	2720		26.67
Aluminum - 7050	2800		27.46
Aluminum - 7178	2830		27.75
Cast iron	7100		69.63
Stainless Steel	7480 – 8000		73.35 – 78.45
Steel	7850		76.98
Zinc	7135		69.97
Plastic / Polymer	**Loads**		
Extruded polystyrene fill	0.7 kg/m^2 (weight of 1cm layer) [7]		
Polypropylene	0.855 g/cm^3, amorphous [7]		
	0.946 g/cm^3, crystalline [7]		
Polyurethane	1.05 g/cm^3 (high-density polyurethane)		
	For flexible polyurethane foam, it varies with how much air is in the foam		

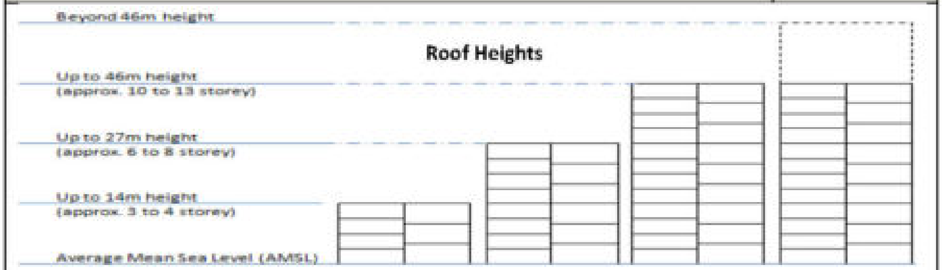
Please refer to:
SS EN 206-1:2009, Specification for concrete
SS 544:2009, Concrete – Complementary Singapore Standard to SS EN 206-1
BS 648:1964 – Schedule of weights of building materials
[1]www.fao.org
[2]http://www.engineeringtoolbox.com/wood-density-d_40.html
[3]http://en.wikipedia.org/wiki/Palmwood
[4]http://www.wood-database.com/lumber-identification/hardwoods/rubberwood/
[5]http://www.engineeringtoolbox.com/density-solids-d_1265.html
[6]http://www.engineeringtoolbox.com/density-materials-d_1652.html
[7]http://en.wikipedia.org/wiki/Polypropylene

TABLE 5 (Equipment load estimates)

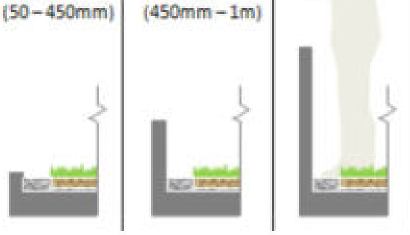
Types of equipment loads	Equipment weight (kg)(Estimates)
Lightweight brushcutter	3 – 10
Lawn mower	10 – 50
Riding mower	200 – 400
Lightweight MEWP[1)] (aerial work platform)	140 – 680*
Heavyweight MEWP[2)] (boom lift)	230 – 500*

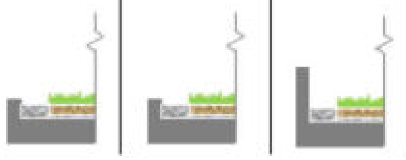
*Weight of equipment + Lift Capacity
1) These equipment are designed to be compactable and can usually lift into a conventional passenger lift
2) These equipment are usually less compactable and usually need to be tolled / driven to site via an access road/surface

TABLE 6 Suggested parapet heights and the associated minimum green roof system's loads & placements, for improved wind uplift resistance (Adapted from ANSI/SPRI RP-14)



Suggested placement(s) of the extensive green roof system	Suggested Parapet Heights – for extensive green roof on different roof heights			
Field of roof Refer to minimum load category **A** (Please also refer to the Building and Construction Authority's requirements on the height of safe protective railings or parapets.)	no less than 50mm (50 – 450mm)	no less than 450mm (450mm – 1m)	no less than 1000mm	Registered PE to design
Field of roof Refer to minimum load category **A** Corners and Perimeters of roof Refer to minimum load category **B**	no less than 50mm (50 – 300mm)	no less than 50mm (50 – 300mm)	no less than 300mm (300 – 450mm)	Registered PE to design





Minimum loads (of the green roof systems) on the roof, to avoid excessive wind uplift:

		Interlocking system	Independent system
A	Green roof Ballast dry weight (inorganic)	49 kg/m^2 (min)	88 kg/m^2 (min)
	Concrete paver weight	49 kg/m^2 (min)	88 kg/m^2 (min)
B	Green roof Ballast dry weight (inorganic)	64 kg/m^2 (min)	104 kg/m^2 (min)
	Concrete paver weight	49 kg/m^2 (min)	104 kg/m^2 (min)

NOTE: Roof corners and perimeters are **no less than 2.6m in width** along roof edges

The above suggestions are with the following assumptions:

- Wind conditions and speeds are within the ranges recorded in Singapore (not more than 33m/s).
- In Exposure B (Dense built urban conditions)

SECTION 3 WIND LOADS ON SKYRISE GREENERY

3.1 WIND CONDITIONS IN SINGAPORE

3.1.1 Sumatra squall (Monsoon winds)

- Skyrise greenery sites are often elevated. In such high rise conditions, stronger winds are expected, especially during the tropical monsoon seasons when strong wind gusts ('Sumatra' squalls) can be experienced.
- The maximum wind gust of up to 100km/h (est. 27.78m/s) has been recorded during a passage of a Sumatra squall.

3.1.2 Mean surface wind speed

- In Singapore, the mean surface wind speed is normally less than 20km/h (est. 5.56m/s).
- The maximum recorded wind speed (in the context of Singapore) is unlikely to exceed 33m/s.
- The following are the wind speeds expected in Singapore.

Wind speed		**relevant Code of Practice**
33m/s	basic wind speed (3 second gust speed)	Code of Basic Data for the Design of Buildings. Loading. Wind Loads – CP3 Chapter V Part 2
22m/s	basic wind speed (hourly mean speed)	Loading for building. Code of Practice for Wind Loads – BS 6399:Part2
20m/s	basic wind speed	Actions on structures. General actions – Wind actions – SS EN 1991-1-4
SS ENs will be the only prescribed design standards with effect from 01 Apr 2015.		

3.1.3 Given Singapore's recorded mild wind conditions, wind loads associated with skyrise greening therefore should not be a major design concern for most rooftop spaces in Singapore. There are however occasional storms of short duration when wind speeds may be exceptionally high, especially at the upper levels of tall buildings. Designers need to account for these occurrences in stabilising plants at high elevations.

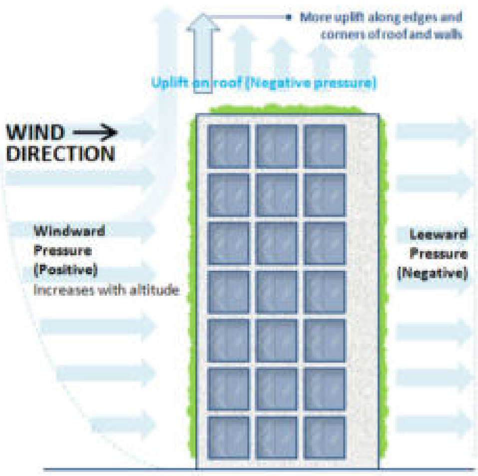
3.1.4 One most immediate concern will be that of rooftop trees/palms/big-shrubs (any tall plants beyond the height of 3m) that are planted right up next to the roof edge, where there is the possibility of plant debris (such as broken branches, etc.) falling from a height. As such, rooftop trees/palms/big-shrubs must be planted away from the rooftop edge by the horizontal distance equivalent, if not more than, the expected grown-height of the rooftop trees/palms/tall-shrubs. Please refer to *CS*

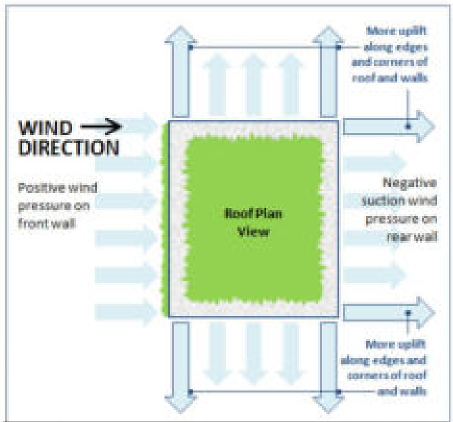
E09:2012, Guidelines on the planting of trees, palms and tall shrubs on rooftop.

3.1.5 Wind conditions in city centers can be complex, as a result of the varying urban volumes of adjacent buildings, which can block, channel and/or concentrate the wind as it passes through, and may not concur with the clear directionality as studied in wind tunnel tests.

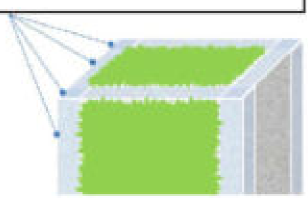
3.1.6 Where uncertain, a registered PE and/or relevant engineering expert should be consulted to determine the wind speed on the building rooftop.

3.2 WIND LOADS ON BUILDING





Usually for both the roof and façade, the building edges and corners are subject to wind pressures of higher intensities. (These can either be positive or negative wind pressures, depending on the wind direction and parapet positions.)



Maximum uplift force on a roof is along the windward perimeter. This occurs when the wind blows at 90 degrees to the perimeter. In general, with increase altitude, more wind load is experienced. Skyrise greenery on higher floors generally receives more wind loads than the lower floors.

3.2.1 In general, wind loads act laterally onto vertical surfaces and building facades.

3.2.2 The roof perimeters and corners are exposed to more wind uplift than the field of the roof. The corners and perimeter areas are where the greatest effects of the disrupted airflow over the building will occur.

3.2.3 Vegetation and finishes at roof corners and along roof perimeters should be monitored for signs of wind stresses (such as mechanically-induced-stress by excessive wind movement of the aerial parts of the plants and wind scouring.) If high uplift pressures are predicted or anticipated, these areas can be hardscaped for walking or furnished into sitting spaces.

3.2.4 Rooftop spaces of buildings facing the sea (or any other such open site environment) are likely to experience higher wind conditions. Similarly, loose materials such as gravels or dry exposed soils installed in these areas may get picked up by the high winds and present a hazard to the rest of the building, neighbouring properties and even people.

3.2.5 On roof surfaces, depending on wind directions and building volume(s), wind loads can be experienced as positive wind pressures or negative wind pressures. Over a large roof area, especially if it has many features and vegetation, wind drag (parallel to the surface) can be significant.

3.2.6

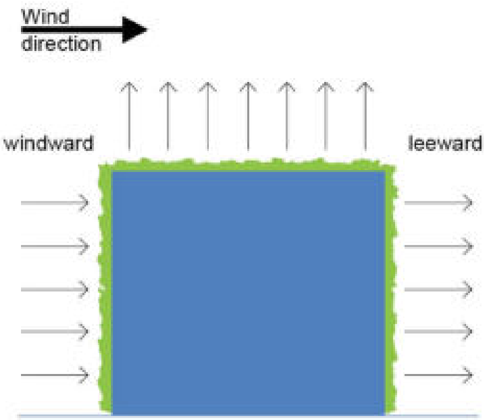
Site factors affecting wind loads on a building	
Geographical location	Either cyclonic or non-cyclonic
Terrain category	The roughness of the building's surrounding environment in dissipating wind forces
Building height	Wind loads generally increase with altitude
Any shielding around the building	Shielding by surrounding volumes and surfaces can have localized effects on the received wind loads
Shape of building	A flat building façade surface generally offers more wind load resistance as opposed to a building surface with openings and overhangs

3.3 WIND LOADS ON VERTICAL GREENERY

3.3.1 On the windward façade, a green wall is subject to positive wind pressure. On the leeward façade, a green wall is subject to negative wind pressure.

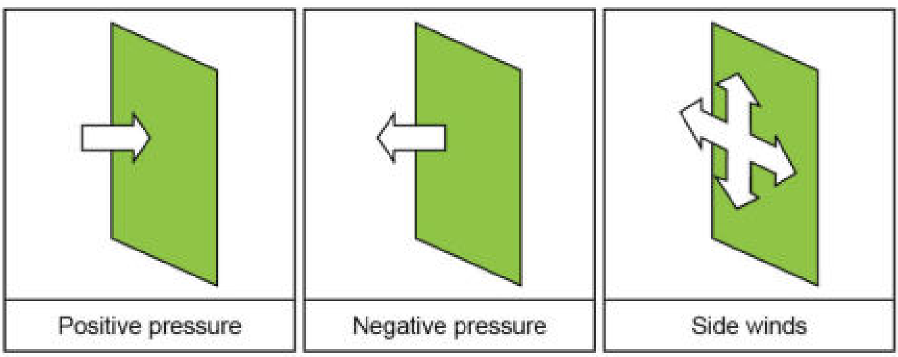
3.3.2 The lateral wind force on a green wall is determined by the following:

- Drag coefficient of the green wall (which can be influenced by the wind direction in relation to the building-form/wall-surface.)
- Total surface area (of the green wall) exposed to the wind force
- The instantaneous wind velocity



3.3.3 Change in wind direction, in relation to the building-form/green-wall-surface, has direct bearing on the drag coefficient. With this potential variation in mind, it is advisable to seek professional advice from a registered PE and/or relevant engineering expert to estimate the wind loads.

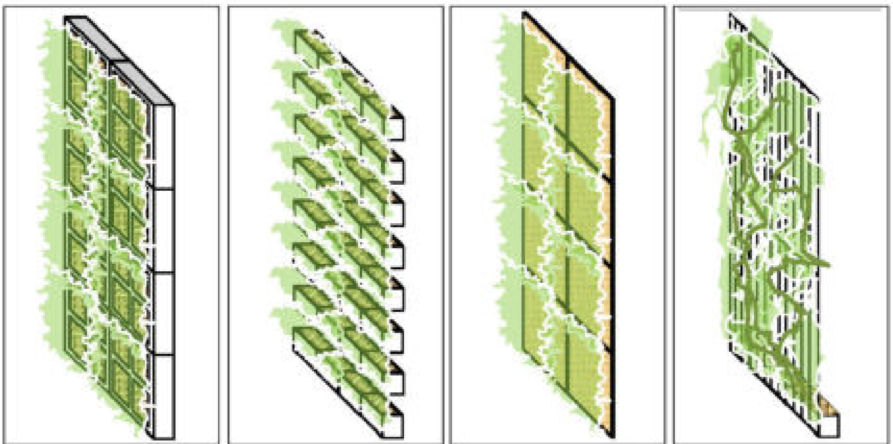
3.3.4 Wind loads on a green wall can be positive wind pressure, negative wind pressure (suction) and/or side winds (wind drag). Negative wind pressure (suction) on a green wall occurs when the wind passes parallel to green wall, threatening to pull the green wall system out from the building façade.



3.3.5 It is general awareness that part of the wind will pass through the foliage of a green wall. However, given that green wall has such diversity of systems types and plant species, the green wall surface should be looked upon as a solid surface when determining wind load.

- BS 6399: Part 2 or SS EN 1991-1-4 is used for the estimation of wind pressures for tall buildings façade design.
- BS 6399: Part 2 or SS EN 1991-1-4 also provides the calculation procedures for determining the local pressure coefficients for typical building components e.g. rectangular plan buildings.

3.3.6 The following are the different types of green wall systems and their associated densities:



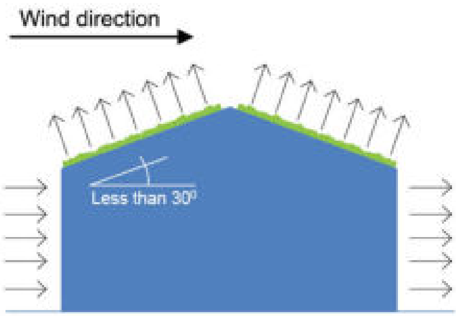
Carrier systems	Planter system	Felt system	Support systems
100 – 120 kg/m2	60 – 100 kg/m2	40 – 60 kg/m2	1 – 50 kg/m2

The above suggested range of densities for various green wall systems can be used in conjunction with BS 6399: Part 2 or SS EN 1991-1-4 to determine the expected wind pressure on these systems.

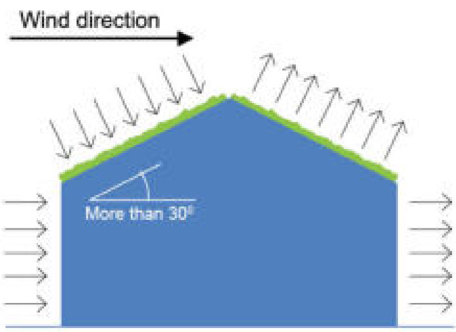
3.3.7 Note however that where the green wall sits in front of an impermeable wall of the building the full resultant load on the green wall and the backing wall will be not more than the total advised by the code plus a margin of 10-20%.

3.4 WIND LOADS ON PITCHED GREEN ROOF

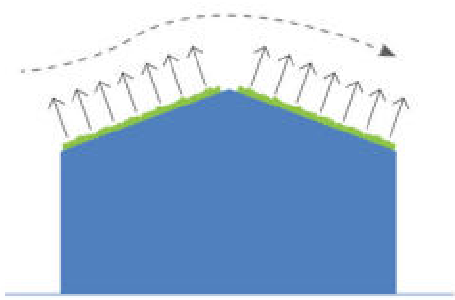
3.4.1 In general, when wind passes over a flat green roof and green roof slope of less than 30 degree inclination, negative wind pressure (uplift) is generated on the green roof surface.

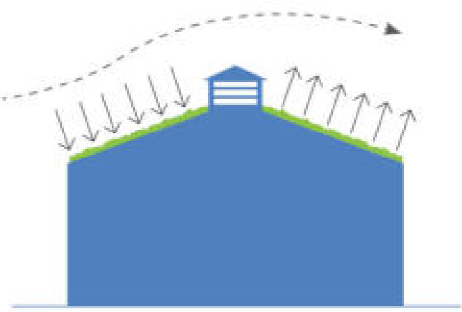


3.4.2 In general, slope on the windward side that is inclined more than 30 degree will experience positive wind pressure. For a green roof system installed on such steeper slope, the resultant negative wind pressures (on the leeward side) will increase the shear (sliding) forces within the green roof system. Please also refer to *CS E08:2012, Guidelines on Design and Construction of Pitched Green Roof*.



3.4.3 Rooftop elements, such as roof protrusion and/or parapet walls can be designed in collaboration with the registered PE and/or relevant engineering experts to mitigate wind uplift of green roof systems.





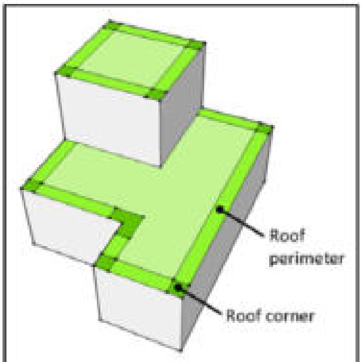
3.4.4 Registered PE can ascertain the shear force(s) within a green roof when the following are estimated:

1. maximum wind speed
2. wind direction(s)
3. roof slope inclination
4. green roof system loads (dry load and wet load)

3.4.5 In general, the steeper the roof, the more shear forces expected between the technical layers within the green roof system. Please refer to *CS E08:2012, Guidelines on Design and Construction of Pitched Green roof.*

3.5 WIND LOADS ON (extensive) FLAT GREEN ROOF

3.5.1 Wind uplift forces are highest along roof perimeters and roof corners. This can be a problem for façade, roof treatments/finishes that are lightweight, including extensive green roof systems.



Note that roof corners and perimeters are no less than 2.6m in width along roof edges

3.5.2 For flat extensive green roof, with inclination no steeper than 7 degrees, Table 6 contains recommendations on the:

- Parapet heights for extensive green roof on various roof heights;
- The minimum dry loads (and placements) of the lightweight green roof system;
- Minimum loads of concrete pavers (and equivalent) along the rooftop edges and corners.

Please also refer to *RTN 2014-04, Parapets to mitigate wind loads on green roofs* at www.cuge.com.sg

3.5.3 Wind pressures along roof perimeters and corners are influenced by the following:

- building height
- roof parapet height
- roof slope
- geographical location
- Building's surrounding site terrain (hills, valleys, escarpments, etc.).

3.5.4 Please read in conjunction with:

- *ANSI/SPRI RP-14, Wind Design Standard for Vegetative Roofing Systems*

3.5.5 Ideally, have roof parapet of no less than 1m (1000mm), for the following benefits:

- Worker safety, when carrying out maintenance work on non-accessible rooftop greenery;
- Mitigation of wind uplifts on rooftop greenery.

3.5.6 Parapet can be designed tall to function as wind-breakers

Where mitigation of wind loads is of concern (in the case of rooftop greenery on skyscrapers), consider parapet more than 1m height. Parapet can also be designed up to 2m in height or more (with vents to manage excessive wind loads) as rooftop features to break up the wind impact. For example, the Marina Bay Sands, roof garden, on the 56th floor, have tall glass parapets to manage the strong wind from the open sea. Wind buffers, in the form of set-back tall shrubs and/or small rooftop trees with open canopies, etc., can also be considered to mitigate rooftop wind conditions.

3.6 WIND LOADS ON ROOFTOP TREES/PALMS

3.6.1 Generally, with increase altitude, stronger wind forces will be experienced. Wind loads on rooftop tree/palm are influenced by the following:

- Tree/palm height
- Crown spread
- Crown porosity
- Wind direction
- Wind speed
- Plant health, etc.

3.6.2 The resultant forces in such dynamic, temporal environment as well as the effects of such forces on the biomechanical stability and integrity of the tree/palm are difficult to ascertain with precision.

3.6.3 Problems of planting rooftop trees/palms on higher altitude:

- Increase wind loads on the crown of the trees/palms stresses the plant
- Falling plant debris from rooftop trees/palms that are planted along the roof edges and corners

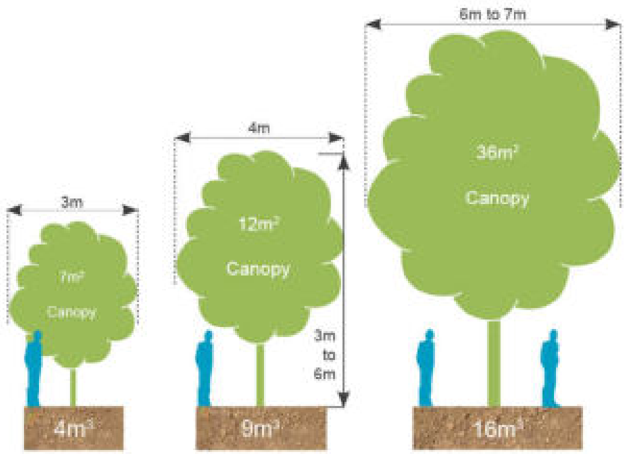
3.6.4 Immediate feasible measures to mitigate the identified issues in section 3.6.3:

- Use small tree/palm species with open canopy
- Do regular tree/palm maintenance (Please refer to *CS E07:2012 – Guidelines on General Maintenance for Rooftop Greenery*)
- Avoid the hazardous situation of falling plant debris by setting back rooftop tree/palm away from roof edge and corner horizontally by the estimated grown-height of the tree/palm
- Provide additional supports to the rooftop trees/palms and resolve the dynamic wind loads by installing 1)rootball anchors, 2)stakes, 3)guylines, etc.
- Please refer to *CS E09:2012, Guidelines on Planting Trees, Palms and Tall Shrubs on Rooftop.*

3.6.5 The following are the estimates on wind loads (drag force) on various tree canopy areas, under different wind speeds, using the Along-Wind Force Equation. Along-wind force can be estimated using the following equation:

Wind Drag force on rooftop tree canopy

Drag force equation: $F = \frac{1}{2}\rho C_D A V^2$



- ρ is air density (1.226 kg m-3)
- A is canopy frontal area
- V is instantaneous wind velocity and
- C_D is drag coefficient (0.3- 0.8)

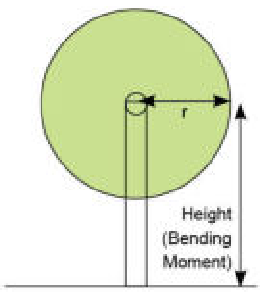
Tree canopy frontal area (m^2)	Wind Loads (drag force) at the following wind speeds			
	(5m/s)	(10m/s)	(22m/s)	(33m/s)
7	50.17 N 0.05017 kN 5.116 kgf	200.7 N 0.2007 kN 20.46 kgf	971.3 N 0.9713 kN 99.05 kgf	2186 N 2.186 kN 222.9 kgf
12	86.01 N 0.08601 kN 8.771 kgf	344 N 0.344 kN 35.08 kgf	1665 N 1.665 kN 169.8 kgf	3747 N 3.747 kN 382 kgf
36	258 N 0.258 kN 26.31 kgf	1032 N 1.032 kN 105.2 kgf	4995 N 4.995 kN 509.4 kgf	11240 N 11.24 kN 1.146×10^6 gf
60	430.1 N 0.4301 kN 43.853 kgf	1720 N 1.72 kN 175.412 kgf	8326 N 8.326 kN 849 kgf	18733 N 18.73 kN 1.91×10^6 gf

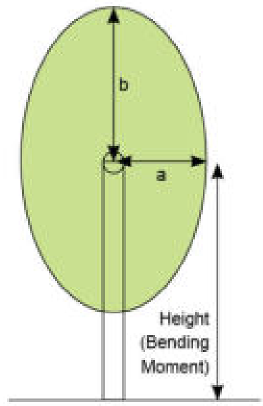
Calculation formula:
http://www.wolframalpha.com/widgets (search for drag force calculator)

The above estimates are with the following assumptions:

- Tree canopy is spherical
- Drag coefficient is assumed to be 0.47 (Tree canopy is assumed to be spherical)
- Air density of 1.226kg/m3

Canopy Frontal Area - calculation	
Of perceived Spherical canopy volume	Of perceived Ellipsoid canopy volume
$\pi \times r^2$	$\pi \times a \times b$





3.7 METHODS OF ESTIMATING WIND LOADS

3.7.1 Wind pressures on buildings and urban spaces are estimated through:

- Standards and codes;
- Wind tunnel test and;
- Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics (CFD)* is increasingly used in analyzing wind patterns and wind effects on buildings and urban spaces. However, the generated wind pressure estimations and readings must be substantiated by a wind tunnel test* and read in conjunction with existing standards and codes. (* - The intended planting on these building surfaces, if any, will not be included in these simulated model tests. This is because the associated drag coefficient of a model tree is unlike a real tree – Model trees are rigid while real trees have structural flexibility, permeability and the aerodynamic characteristics of real tree species in response to wind forces have yet to be widely studied.)

3.7.2 Engage an Environmental Sustainable Design (ESD) engineer/consultant to simulated skyrise wind conditions using computational fluid dynamics.

3.7.3 Codes and Standards

In Singapore, for estimations on imposed roof and wind loads, reference should be made to:

- Loading for Buildings. Code of Practice for Wind Loads - BS 6399: Part 2
- Loading for Buildings. Code of Practice for Imposed Roof Loads - BS 6399: Part 3
- Actions on structures — General actions — Part 1-4: Wind actions - Wind actions – SS EN 1991-1-4
- Actions on structures. General actions – Densities, self-weight, imposed loads for buildings – SS EN 1991-1-1

References

FM Global 35-1 - FM Global Property Loss Prevention Data Sheets – Green Roof Systems

ASTM E2397 - Standard Practice for Determination of Dead Loads and Live Loads Associated with Vegetative (Green) Roof Systems

ASTM E2399 - Standard Test Method for Maximum Media Density for Dead Load Analysis of Vegitative (Green) Roof Systems

BS 648 - Schedule of Weights of Building Materials
BS 6399: Part 1 - Loading for Buildings. Code of Practice for Dead and Imposed Loads

http://toolboxes.flexiblelearning.net.au/demosites/series10/10_01/content/bcgbc4010a/01_loads_loading/01_primary_loads/page_003.htm

Work Safety and Health Guidelines – *Working Safely on Roofs*

ANSI/SPRI RP-14, Wind Design Standard for Vegetative Roofing Systems

Workplace Safety and Health Guidelines – *Anchorage, Lifelines and Temporary Edge Protection Systems*

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