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Retrofitting of pedestrian overpass by Truss-Z modular systems using graph-theory approach

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ABSTRACT

Installing pedestrian ramps is a common improvement towards a barrier-free environment. This paper introduces a graph-theoretical method of retrofitting of a single-branch Truss-Z (TZ) ramp in a constrained environment. The results produced by this exhaustive search method are usually ideal and better than those produced previously with meta-heuristic methods.

A large case study of linking two sections of the Hongo Campus of Tokyo University using an overpass in an extremely constrained environment is presented. TZ modules with 1:12 (8.3%) slope are used, which is allowable in most countries for ramps for self-powered wheelchairs.

The results presented here are highly satisfactory both in terms of structural optimization and aesthetics. Visualizations of the TZ ramp system, composed of 124 units, are presented.

1. Introduction

The stairway is the most common means of pedestrian vertical transportation used in the built environment. Elevators and escalators are relatively expensive to install and maintain, and their traffic flow capacity is much lower than that of stairs. Moreover, it is not always possible to install an elevator or escalator due to limited space. However, most people occasionally or temporarily cannot use stairs, as when riding a bicycle, pushing a baby stroller or carrying heavy luggage. For elders and people in wheelchairs, stairs form a permanent and impassable barrier. This is an important social issue, especially since the proportion of elderly people in society is higher than in the past, and some predict that this tendency will continue [1].

With aging, individuals suffer from thinning of bones, muscle disorders, exhaustion, balance and strength problems, and sight and hearing disorders [2,3]. All of these put elderly people at risk in city environments because of their decreased movement capabilities, space perception and mental capacity [4]. For a comprehensive review of the literature on the elderly pedestrians, see [5]. Awareness about these problems is growing among designers and planners. Building code upgrades tend to reflect this fact, such that new constructions usually better fit the needs of seniors. However, it is also a common perception that an average existing built environment is not "barrier-free". Making the environment more suitable for elders and people with disabilities improves the quality of life not only of the aforementioned groups, but, in most cases, that of everyone in society. The realization of such upgrading is, however, often challenging technologically and economically. Modularity and prefabrication are common ways of economizing on construction costs, which inspired the creation of TZ: the universal and inexpensive reconfigurable ramp system.

This is an updated and revised version of the conference paper [6], which introduced the concept of an automated retrofitting of TZ structures to a given environment. The methodology presented in [6] was based on evolutionary algorithms, and the results were rather satisfactory. This paper presents a new, graph-theoretical method, which is capable of producing better, in fact, *ideal* solutions. The TZ ramp presented in [6] was based on modules with a 1:8 slope, which is not suitable for wheelchairs. A new, much larger and more realistic case study, where the slope of the TZ ramp is allowable for wheelchairs (1:12), is presented.

1.1. The Truss-Z system

Truss-Z (TZ) is a modular skeletal system for creating free-form ramps and ramp networks among any number of terminals in space

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[7,8]. The underlying idea of this system is to create structurally sound provisional or permanent structures using the minimal number of types of modular elements. The TZ structures are composed of four variations of a single basic unit (*R*), as shown in Fig. 1.

Unit *L* is a mirror reflection of unit *R*. By rotation, they form two additional variations (*R2* – rotated *R* and *L2* – rotated *L*). Most conventional constructions have symmetries, which can be used to substantially reduce the computational effort of structural computations. In the context of this paper, particularly relevant are the graph-theoretical methods described in [9,10]. According to [11], *the symmetry of a body is described by introducing the set of all those transformations which preserve the distance between all pairs of points of the body and maps the body into coincidence with itself*. It is possible to create TZ configurations of all types of symmetries, as shown in Fig. 2.

Nevertheless, in the general case, which is considered here, only identical symmetry is applicable.

Recommendations for the slope of pedestrian ramps depend on the intended use and local regulations. For example, the Americans with Disabilities Act (ADA) requires a 1:12 (8%) slope for wheelchairs and scooters on ramps for business and public use [12] British guidelines, as recommended by the Disability Discrimination Act (DDA) and Disability Rights Commission (DRC), are 1:6 (16%) for temporary ramps for assisted wheelchairs, 1:12 for temporary ramps for self-powered wheelchairs, and 1:15 (7%) for permanent and semi-permanent ramps [13]. In this paper, the slope of the TZ module (TZM) is set to 1:12 (8.3%).

TZ structures can be optimized for various criteria: the minimal number of TZMs, the minimal number of changes in direction, and, in a case of multiple branches, the minimal network distance. Because the system is modular, the corresponding problems are discrete optimizations. Various deterministic and meta-heuristic methods have been successfully implemented. Namely: backtracking [14], evolution strategy [15], and evolutionary algorithm [16,17]. These methods produced usually rather good, but not *ideal*, results. This paper presents a graph-theoretical exhaustive search [18] method, which is substantially more computationally expensive than aforementioned meta-heuristics, but produces the best allowable, *ideal* solution(s).

1.2. The graph-theoretical methods in engineering and architecture

Graph theory (GT) has been applied to various problems in the built environment, including modeling 3D objects [19], representing architectural functional layouts [20], floor plan analysis and recognition (for architects to find similar projects) [21], retrieval of engineering drawings by their shape appearances [22], building information modeling (BIM) at early stages of design [23], 2D geometric constraint solving [24], analysis of fundamental properties of skeletal structures, such as connectivity [25] and rigidity [26], 3D finite element analysis [27], modeling of cable-membrane structures [28], reliability analysis of structural systems [29], generation and selection of manufacturing processes [30,31], path finding in crowd simulations based on the Dijkstra algorithm [32], or its extension – A^* [33], search algorithm [34], and reliability analysis [35], to name a few.

GT has already been used to analyze certain topological properties of TZM [7]. Backtracking [36], a classic depth-first search strategy, has been implemented for finding quickly allowable solutions, which however, are usually far from the best ones. In the following section, for clarity, the problem is reduced to the projection on the 2D plane.

2. The graph-theoretical method for optimization of a planar layout of a TZ structure

A single trapezoid, called 1, which corresponds to units *R* and *L2*, and its rotation, called 0, which corresponds to *L* and *R2*, together allow the creation of a path of any planar trajectory, as shown in Figs. 3 and 4. For a corresponding interactive demonstration, see [37].

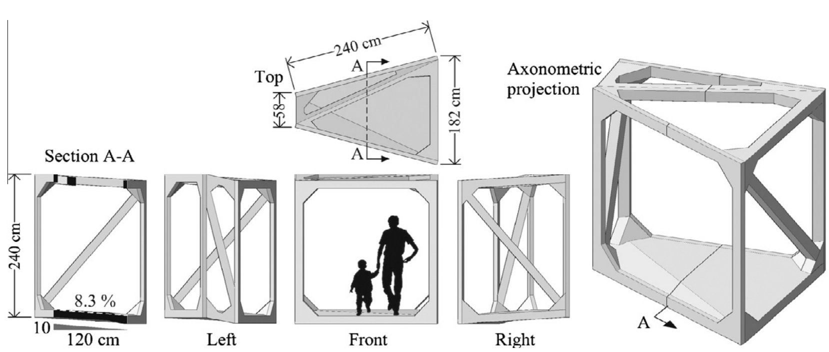

Fig. 1. The section showing the slope followed by the planar and axonometric projections of the TZ basic unit (*R*).

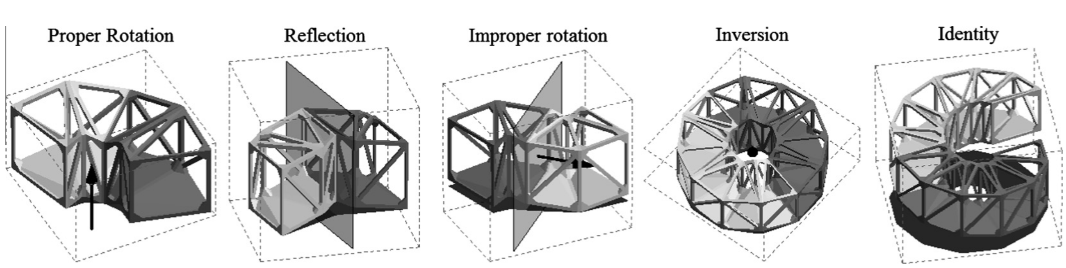

Fig. 2. The symmetry operations. From the left: (1) Proper rotation – the axis of rotation (AOR) is indicated by the black arrow. (2) Reflection – the reflection plane (RP) is shown in gray. (3) Improper rotation – RP and AOR are shown in gray and as the black arrow, respectively. (4) Inversion – the center of inversion is shown in black. (5) Identity – no other symmetry operation is possible.