Case Studies in Construction Materials xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm

Case study

An experimental study on the lateral pressure in foam-filled wall panels with pneumatic formwork

Bijan Samali[a], Saeed Nemati[a], Phezhman Sharafi[a,*], Mojtaba Abtahi[a], Yahya Aliabadizadeh[b]

[a] Centre for Infrastructure Engineering, Western Sydney University, Australia
[b] University of Maryland, College Park, Maryland, USA

ARTICLE INFO

Article history:
Received 2 July 2018
Received in revised form 24 September 2018
Accepted 24 September 2018

Keywords:
Flexible formwork
Lateral deformation
Pressure
Polyurethane foam
Fabric formwork

ABSTRACT

Applications of structural wall panels using flexible formwork systems have recently attracted the attention of architects and engineers. Many of such panelised systems in the market are foam-filled walls, mainly presented in the form of sandwich panels. Knowledge of cast-in-situ induced lateral pressure on the formwork is critical for the economical and safe design of flexible formwork for construction. Formwork cost, on the other hand, comprises a high proportion of the total cost of a building constructed by cast-in-situ materials. Although extensive research has been conducted on the lateral pressure of concrete formwork, the components and mechanics of the lateral pressure in foam-filled walls have not been thoroughly understood. This paper will investigate the lateral deformation, and then lateral pressure on flexible fabric formwork used for construction of polyurethane foam-filled panels. From the lateral pressure on the formwork, the tension forces in the ties are calculated by measuring the compressive force developed between the formwork edges. The results are used for design of intermediate ties for controlling the lateral deformations in an innovative foam filled panelised system, which has been designed for rapid assembly of semi-permanent buildings for post disaster housing.

1. Introduction

In construction industry, formwork is a temporary or permanent mould, into which concrete or other similar materials are poured. It is used to form concrete into structural shapes such as beams, columns, slabs, shells, etc. in a structure. Construction using cast-in-situ structural elements relies on various formwork systems offering the opportunity to create economic structures with almost any geometry. Yet, formwork is one of the critical elements impacting construction efficiency and planning, and accounts for a significant part of the total construction time and cost [1]. The cost significantly varies bases on the type of formwork and construction method [2]. A great majority of structural wall panels, used in building construction, are filled with concrete or concrete foams and casted-in rigid formworks. The design methods for such formwork systems are established in the literature.

There are several parameters playing significant roles in formwork selection process, such as accessibility, fabrication cost, assembling and dismantling cost, total and special weight, mechanical properties, and geometric formability. On the other hand, many of the traditional formwork systems suffer disadvantages, such as low productivity, labour intensiveness,

* Corresponding author.
E-mail address: p.sharafi@westernsydney.edu.au (P. Sharafi).

https://doi.org/10.1016/j.cscm.2018.e00203

and long cycle times. As an alternative, flexible formwork made of specific fabrics (also known as fabric formwork) is a sustainable construction system for optimised cast-in-situ geometries with lower cost, higher durability, and potential for a variety of architectural designs [3–6]. Therefore, there has been increasing interest in the use of fabric formwork as an alternative for the conventional steel, aluminium or timber formworks [7].

Fabric formwork is made of textile sheets of synthetic fibres such as nylon, polyesters, polypropylene that are fabricated into containers to hold various type of fillers such as concrete during its placement and curing. These flexible moulds offer good flexibility in design and construction. Using fabric formwork as a mould for cast-in-situ structures elements such as concrete structures, it is possible to: (1) cast architecturally interesting, structurally optimized non-prismatic structures that use up to 40% less concrete in comparison with an equivalent prismatic section [8]; (2) offer potentially significant embodied energy savings [9]; and (3) achieve a striking reduction in the CO_2 emissions [10–12]. Formwork must support all loads (dead, imposed, environmental, etc.), which may be applied until these loads are carried by the cast-in-situ structure itself. Although fabric formwork enables creating iconic and revolutionary forms based on natural laws of the catenary, when it comes to structural applications some obstacles limits their practical applications. From the structural engineering point of view, formworks should be designed for different ultimate and serviceability loads including the lateral pressure of filling materials [13].

Most codes determine the lateral formwork pressure resulting from casting of fresh concrete, to be equal to a full water head of concrete. This hydrostatic model is very conservative; because it considers the cast-in-situ material to be a fluid, where the lateral pressure on the formwork follows a hydrostatic distribution with that material's density. Such specifications are safe, but they are too conservative and therefore uneconomical. Cast-in-situ or a filled mould exerts a hydrostatic pressure on the formwork. The flexible formwork assumes the geometry required to resist this load is dictated by both the fluid pressure and internal stresses in the formwork material. In this way, the final shape of the casting can be controlled by pre-stressing the formwork or selecting the desired formwork stiffness characteristics. The lateral pressure of concrete on different formwork materials has been widely studied in the literature, models and formulae have been suggested in design standards [14,15], and some reviews and discussion have been presented in this respect [16–18].

McCarthy et al. [19] showed low plastic viscosity of filling material increases the lateral pressure, and enhancing workability increases the formwork pressure. Khayat et al. [20] showed formwork pressure exists as long as filling material is in a plastic state and its rate of decay is related to the rate of the stiffening of filling material. On the other hand, they showed the placement rate and method are critical to formwork pressure; i.e. the higher rate of placing, the higher lateral pressure. They showed that pumping into the formwork from the bottom of the form exhibits higher pressures than that placing from top. Their research revealed that rigid and smooth formwork materials result in higher lateral pressure and lower rate of pressure drop after placement. Hanna [14] studied the functions of tie rods to resist the tensile forces resulting from the pressure of fresh filling material. Teixeira et al. [21] analysed the effect of casting rate on the maximum lateral pressure exerted by self-compacting concrete on vertical formworks. Zhang et al. [22] showed that slump, casting speed, and vibration mode can greatly influence the formwork pressure. Wolfgang et al. [23] showed a lower rate of placement can result in lower lateral pressure. Assaad et al. [24] found the lowering the casting rate has no significant effect on the rate of pressure drop in time.

There is not much data pertaining to the effects of formwork dimensions on lateral pressure [25]. For instance, the influence of formwork dimensions on lateral pressure was evaluated using experimental test by Khayat et al. [26]. Test results showed that the scale effect has an influence on the rate of drop in lateral pressure with time. Rodin [27] reported that the maximum pressure appears to be lower in formwork systems of smaller cross-sections. Gardner [28] demonstrated that the larger dimension of the formwork, the larger lateral pressure from conventional vibrated concrete. Omran et al. [29] presented the influence of formwork width, shape and surface material of formwork on lateral pressure characteristics. The results revealed that the increase in formwork width can increase the initial lateral pressure and delay the time needed for the formwork removal.

Although the density is the most important factor in lateral pressure on formwork, in foam-filled structures, parameters like the gel time and expansion rate affect the foam pressure distribution. Knowing that the expansion ratio of PU foams is the ratio between the volumes of a given amount of the components in liquid form compared to the volume of the same amount of substance in solid form, one could have expected that the density controls structure and related properties. Any increase in core density results in improvement in compressive test results [30]. Goods et al. [31] also reported the mechanical properties depends on density following a power-law relationship. This dependency and relationship between density and mechanical, morphological, insulation, and dimensional stability of polyurethane foams have been investigated by various research groups [32–34]. As the blowing agent increases, the pore sizes decreases and because they act as a nucleating agent, it induces narrow size distribution. Gelation time also controls pore size distribution and reflected final mechanical properties [35]. Despite a relatively large amount of literature on the lateral pressure of traditional materials such as fresh concrete on conventional formwork systems, when it comes to such information about foam filled panels, the literature is almost silent. On the other hand, the hydrostatic model is too conservative as it considers the foam to be a fluid, establishing that the lateral pressure on the formwork follows a hydrostatic distribution, related to the foam density. This is the focus of this study, where the lateral pressure of foam on the flexible formwork of different sizes will be investigated. Then, the intermediate ties for securing the formwork against lateral pressure are designed accordingly.