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Wall panel renaissance: tilt-up concrete construction

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Tilt-up is a site-based construction method which involves casting large concrete panels horizontally and tilting them into place to form walls or other building elements. Tilt-up is typically used for low-rise buildings, in particular 'shed' type structures, up to a maximum of about four storeys. The technique is said to have originated in the USA, where it is now used for about 7000 buildings per annum. Although tilt-up is used in over 100 countries, including the USA, Australia and New Zealand, to date it has been used for few buildings in the UK, although at least ten are currently under consideration. On the basis of findings from a PhD research project, the paper outlines the development of the current design and construction methods for tilt-up, including structural and architectural design for panels, on-site 'best practice' and the most effective means of delivery for tilt-up. Design considerations are analysed and important aspects of the construction process are highlighted to explain the key issues in the practical application of this technique. A summary of construction cost data and results of an attitudinal survey are also presented. The paper includes original findings from research on tilt-up and concludes with recommendations for future use of the technique in the UK.

Keywords: buildings, structure & design; concrete structures; research & development

Introduction

Concrete panels can be cast *in situ* or precast, either in a factory or near to their final location on the construction site. The generic term 'tilt-up' is used specifically to describe concrete panels that are cast horizontally on site at a short distance from their final location in the building structure, and then tilted into place. In some instances, the wider terms 'site-precast', 'site-cast precast', 'tilt-slab' or simply 'tilt' are used to include structural applications such as beams, columns and frames. Tilt-up has been used in the USA, Australia and New Zealand since the early 1900s, and has spread to over 100 countries worldwide. In some states of Australia, tilt-up accounts for 95% of all low-rise buildings. In the USA, 23 million square metres of panels were erected in 1998 and the market for tilt-up almost doubled in three years from 1996 to 1999. The reinforced concrete panels can be load-bearing or non-load-bearing, are typically 7–9 m high and weigh about 20–25 t.

2. The technique is used for low-rise industrial and commercial buildings, where it offers speedy and economical 'hard wall' enclosures, but it is also used for residential and leisure projects. The principal advantage of tilt-up is economy, but speed of construction, attractive appearance, sound insulation, robustness, security, fire resistance and thermal performance are also important. Many design tools are available to aid the design of panels for erection, construction and in-service conditions. Preplanning of the construction programme enables the design team to take advantage of what is essentially a factory production process on site to achieve economical and attractive tilt-up structures. The implications of these and other issues are covered in later sections; the first part of the paper provides an overview of the development of tilt-up construction.

Historical development

3. Although some claim that the origins of tilt-up can be found in the Middle East, the general opinion is that versions of tilt-up began in the USA[1] in the early 1900s, a few decades after major advances in reinforced concrete technology by engineers such as Ernest Ransome.[2] Until about 1895, the spread of reinforced concrete technology in the USA was hampered by a lack of high-quality cement and the dominance of a powerful steel industry.[3] But in the earliest years of the twentieth century, concrete technology developed apace, many pioneers explored new construction ideas, and both the Portland Cement Association (PCA) and the American Concrete Institute (ACI) were established.[4]

4. Although it is not clear when or where the first tilt-up building was erected, several entrepreneurs were known to be among the first to use site-batching and rudimentary lifting equipment on site. Thomas Edison used a track-mounted crane to lift tilt-up panels for housing in New York as early as 1906.[5] However, mobile-crane technology was in its infancy and so tilting tables were used more frequently. Colonel Robert Aiken, credited as the first tilt-up pioneer, constructed several buildings in

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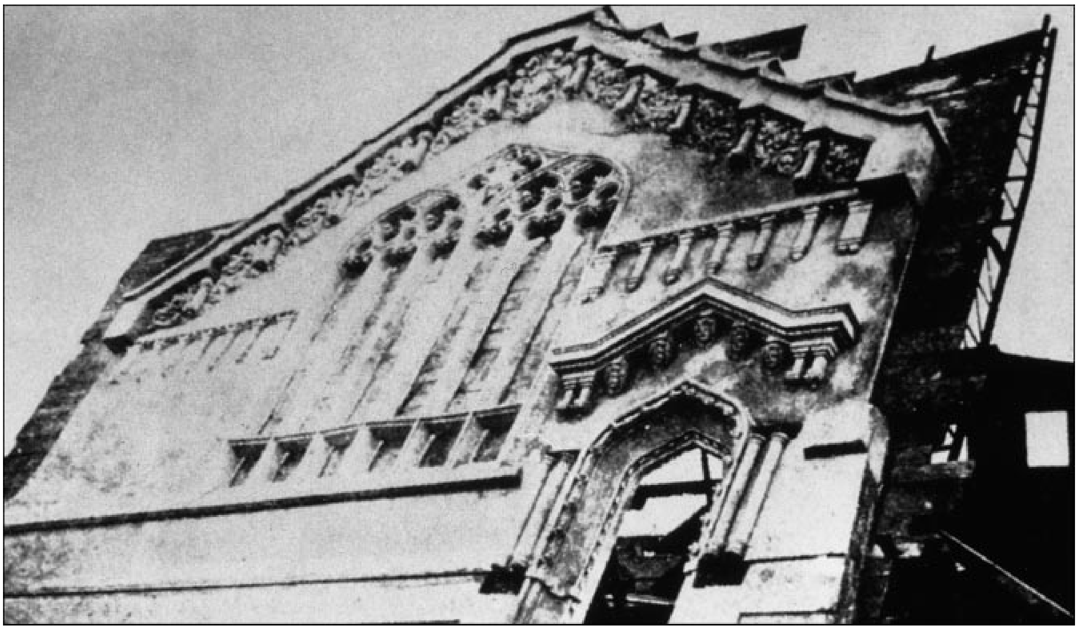

Fig. 1. Zion Memorial Church, Illinois, 1910 (courtesy Portland Cement Association)

Fig. 2. Scripps Community Buildings, La Jolla, California, 1914–16

Illinois and Ohio between 1905 and 1910 using tilting tables up to 23 m long and 8·2 m high. Aiken's Zion Memorial Church of 1910 still stands today[6] (Fig. 1). It is thought that US Army tilting equipment was used by the architect Irving Gill to construct tilt-up buildings in California, including the Scripps Community Buildings at La Jolla.[7] This single-storey building featured 18 m long plain concrete facades with arched openings (Fig. 2). A tilt-up house by the architect R. M. Schindler,[8] built in Hollywood in 1921, also remains influential. In this example, tilt-up enabled Schindler to create a wall with 'repose . . ., but without heavy, confining qualities' (Fig. 3).

5. During the following decades, the Depression and the Second World War stifled growth in construction in the USA, but the rush to house servicemen created an opportunity for tilt-up in the early 1950s. This coincided with the emergence of truck mixers and mobile cranes, and a much-needed series of 'know-how' pamphlets on tilt-up that covered building design, construction schedules, processes and costs. This early work marked the first stage of development of design methods for tilt-up,

Fig. 3. Kings Road house, Hollywood, California, 1922

which continued with the initial report from ACI Committee 551 (Tilt-up) in 1979, and the publication of Brooks's comprehensive *Tilt-up Design and Construction Manual*.[10] These publications on tilt-up became widely available to contractors within the USA, and to interested parties elsewhere. In Australia and New Zealand, for example, work to promote and develop tilt-up by the Cement and Concrete Associations there was strengthened by links to experienced American contractors and equipment suppliers.

6. The architectural design of tilt-up buildings has also evolved. Early buildings tended to be quite boxy in appearance with little surface texturing or colour, but experimentation during the 1970s and 1980s resulted in some quite elaborate examples, particularly in 'Silicon Valley' in California. Exposed aggregates, hand-laid slates, trompe l'oeil painted motifs and mosaics have all been used, but panels with more modest architectural expression seem to have been more popular in recent years (Fig. 4). So, in the last 90 years, tilt-up has evolved from a small-scale construction method to a reliable, flexible and well-understood technique. Tilt-up is now used throughout the world, in very different climates and cultures, for many different sizes and types of buildings. By the early 1990s, tilt-up accounted for 15% of the annual industrial construction market in the USA, with the largest single building measuring over 150 000 m^2 in floor area.[11]

7. Despite this success, tilt-up has made more progress in some countries, such as Canada and the USA, than in others, such as the UK and the Republic of Ireland, where there are comparatively few such buildings in existence (approximately twelve warehouses, plant rooms and residential blocks in total). None the less, anecdotal reports of interest in the advantages of concrete construction for durability, appearance, fire resistance and passive cooling indicate that there may be significant

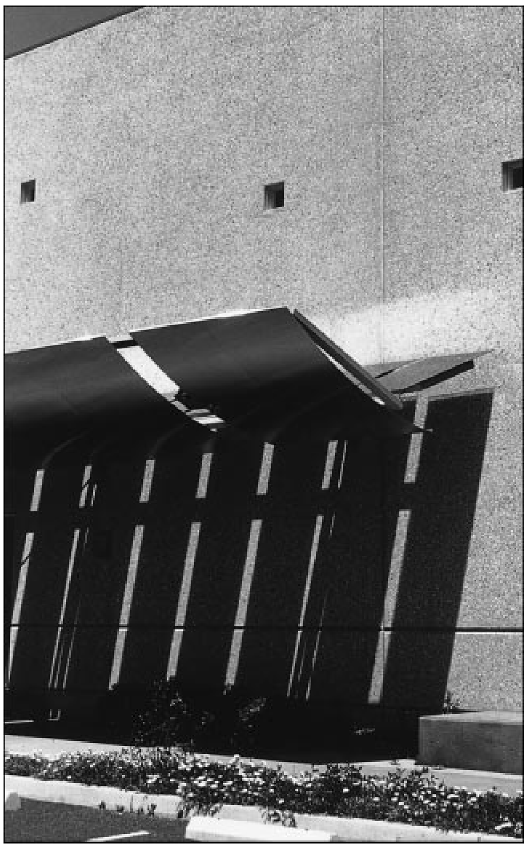

Fig. 4. Contemporary tilt-up: APS factory, California

potential for tilt-up in the UK. There is also an increasing willingness to investigate and implement new ideas or processes, as shown by interest in initiatives such as 'lean' construction. The PhD thesis[12] on which this paper is based evaluated the reasons for the anomaly of slow adoption of tilt-up in the UK. The research included an overview of design principles, construction processes, and performance issues relating to tilt-up, together with an analysis of construction costs in the form of a predictive model and an attitudinal survey of people's perceptions of tilt-up undertaken by way of a programme of personal interviews. The findings are outlined in the following sections.

Design principles

8. Both plain and sandwich wall panels are normally designed as fully load-bearing, although non-load-bearing cladding panels are used occasionally. Typically, building stability is achieved using the tilt-up panels as shear walls, with the roof acting as a diaphragm.[13] Tilt-up's load-bearing panels can support a roof and suspended floor slabs. The basic process of tilt-up construction is illustrated in Fig. 5, from which it is clear that the slender panels are subjected to three distinct conditions: erection (during lifting), construction (when propped or braced) and in-service loading. The ultimate tensile strength of the concrete is perhaps one of the most important factors for tilt-up, because the lifting process normally relies on the bending strength within the concrete rather than its reinforcement. Therefore, instead of the 28 day compressive strength (32–40 MPa for tilt-up), the time between casting and lifting and its effect on the early ultimate tensile strength is often more important.[14]

9. With tilt-up, the amount and location of reinforcement depend on panel height, thickness (i.e. slenderness ratio) and loading. Reinforcement is placed centrally in a single layer, except around openings, around lifting or bracing inserts and in panels erected in earthquake areas. According to practitioners, there can be a delicate balance between having a single layer, and adding an extra layer of fabric and saving 15 mm of concrete. In countries where a tilt-up code exists, a minimum area of reinforcement is usually stated (0·1–0·25% being the typical range). Recent UK research findings[15] suggest a value of 0·26% should be sufficient to satisfy design codes in this country. Lifting design is based on the assumption that the panel is uncracked and that the flexural stress is the most important factor; the flexural stress is limited to $0{\cdot}36\sqrt{f_{cu}}$ (where f_{cu} is the compressive strength at the time of lifting). The loads encountered during the lift can be complex; the panels are slender (typically with a slenderness ratio of 40–50), and the strength of the concrete is relied on to resist bending moments and flexural stresses, which can be four times as great as those experienced under normal in-service conditions.

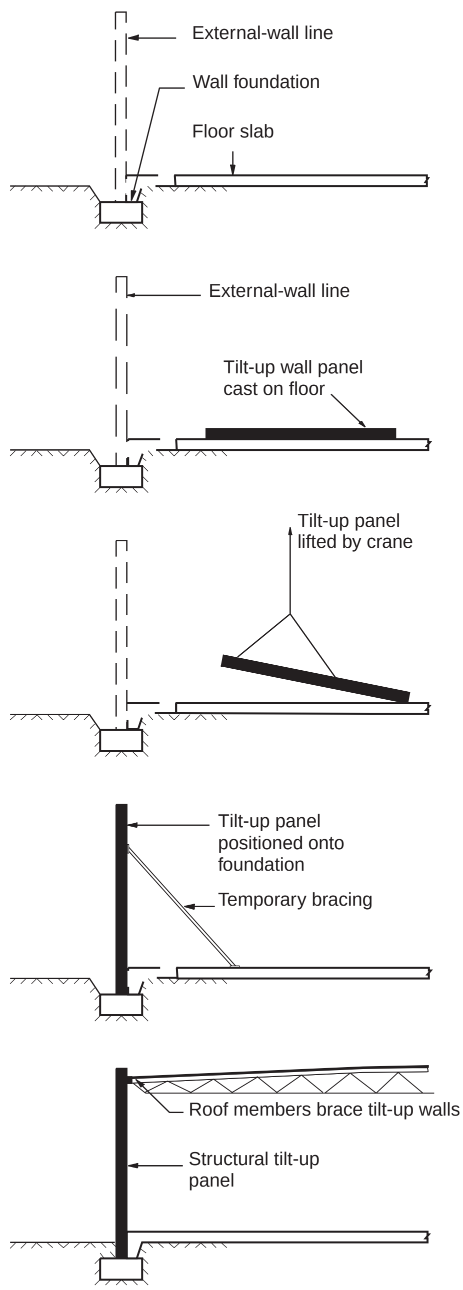

Fig. 5. The tilt-up process (courtesy Reinforced Concrete Council)

10. The intensity and direction of these forces depend on panel weight, rigging arrangement, suction between the panel and casting bed, inclination at lifting, and swinging on release; use of a computer program from a lifting-equipment supplier is advisable.[16,17] Having sketched the tilt-up panel in outline, the engineer can use a computer program to determine if the panel design and location of lift points result in stresses within the tensile strength of the concrete, adjusting the design or adding reinforcement where necessary.

11. It is usual to design lifting inserts symmetrically about the centre of gravity in the horizontal direction (so that the lift will be

level), and above the centre of gravity in the vertical direction (so the panel will tilt, not lie flat (Fig. 6)). Lifting-insert design is usually carried out by the manufacturer, taking into consideration the dimensions, concrete strength, rigging and size of crane to be used. After lifting, the tilt-up panel is held securely by braces until such time as the remainder of the panels and roof structure are in place to 'tie' the building together. Temporary braces are used to restrain the panel against transverse loads such as wind forces. A minimum of two props per panel are attached between the panel and slab. These must resist the overturning forces, which depend on wind velocity, surface area, openings and the angle of bracing (Fig. 7).

12. In the UK, panels are generally designed to BS 8110 in respect of materials, specifications and construction, and structural design. A compatible design approach, accommodating international experience in the design and performance of tilt-up wall panels, in addition to full-scale tests, has been given by Southcott and Tovey.[15] Panels are commonly slender but lightly loaded axially, and so lateral loads dominate.[18,19] The above tests have shown that arbitrary slenderness limits are unnecessary provided the analysis takes account of P–delta effects.[20] These are bending moments resulting from vertical loads on slender panels. A simple design method is given for height-to-thickness ratios of up to 50. For height-to-thickness ratios of 50–60, additional serviceability checks to satisfy cracking and deflection control are described.[15]

13. In principle, most tilt-up panels are designed as simply supported members, with the roof acting as a diaphragm to carry transverse forces to shear panels at 90° to one another (Fig. 8). Occasionally, panels are designed as propped cantilevers. The design for in-service loading also considers vertical loads from the floors and roof, wind loads, and movements caused by concrete shrinkage or thermal movements. In contrast to the lifting condition, reinforcement has a part to play in controlling shrinkage and temperature effects and in resisting in-service loads.[15]

14. So, design methods compatible with UK codes have been identified for the erection, construction and in-service conditions of tilt-up. The next section assesses how effective planning of construction activities can capitalize on the efficient structural design of the tilt-up panels.

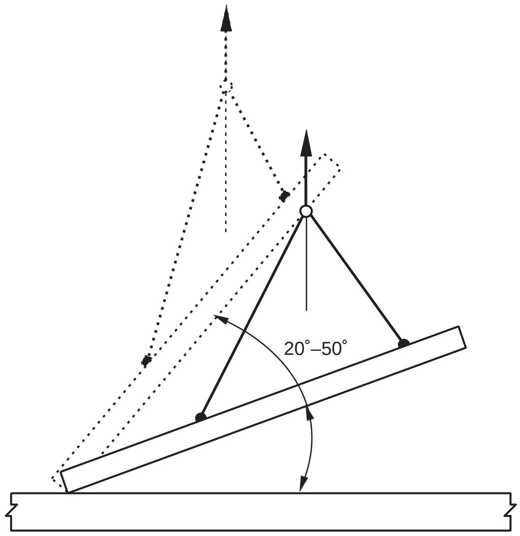

Fig. 6. Critical position for maximum bending moments and stresses (courtesy Reinforced Concrete Council)

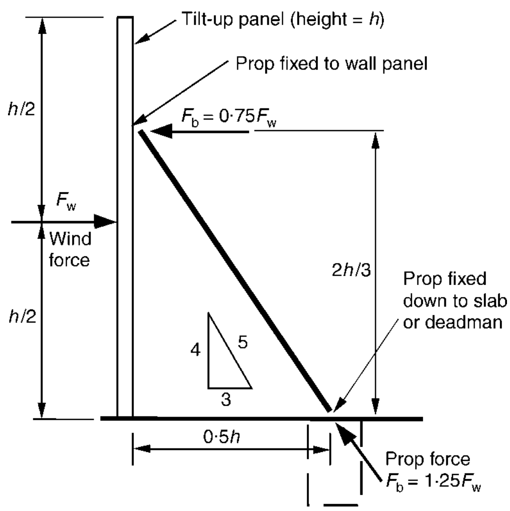

Fig. 7. Typical bracing set-up (courtesy Reinforced Concrete Council)

Construction process

15. It is generally understood that effective construction planning can produce more efficient site activity, and with tilt-up this is particularly true. The nature of the process means that inaccuracies in the design, or in work carried out on site, can be costly, particularly if expensive items such as cranes are left idle on lifting day. Thus, the best results in tilt-up are where the design and construction teams work closely together, in which case tilt-up may lend itself to certain contractor-led or partner style procurement routes. For this reason, design engineers need to appreciate the basic site processes in erecting a tilt-up building.

16. In tilt-up construction, the ground slab of the building often forms the casting bed for the panels. Following construction of the groundworks and substructure, the floor slab is cast to a flatness appropriate to the casting method and required finish of the tilt-up panels. The quality of the casting areas should be, at least, of a specification equal to that of the tilt-up panels.[21] Achieving a good-quality floor finish is aided by laser screeds, but floor joints and crane operating positions also warrant early consideration. Although it is usual for panels to be cast individually on the slab, stack casting of panels (up to 900 mm high) is a popular option for smaller sites and may use temporary casting beds where more appropri-

ate. Timber or metal formwork is used for individual and stack casting, and the casting slab is treated with a chemical bond breaker/cure coat prior to pouring the concrete. This product enables release of the panels from the slab and formwork, and is particularly suited to tilt-up as it degrades under ultraviolet light when the panel face is exposed. One of the key advantages with tilt-up is that only minimal edge formwork is required for casting, unlike the extensive vertical shuttering used for casting the equivalent wall panels *in situ* or in precasting in a factory.

17. For insulated tilt-up sandwich panels, casting is a three-stage process; in these panels, fibre composite or metal pins are used to connect two separate leaves of concrete. Insulation is laid on top of the wet concrete of the bottom (outer) layer and fibre ties are inserted through predrilled holes in the tightly butted sheets. Having twisted the ties into place, workers tread lightly over the insulation to expel any remaining air. With metal anchors, these ties are attached to the reinforcement cage before casting the bottom layer of concrete. Such proprietary tie systems aim to minimize cold bridging and ensure consistent location of the insulation material.

18. Once cast, minimum curing periods for tilt-up are typically between three and seven days, depending on the weather, mix and strength required for lifting.[22] Given that the slab and panel casting operations normally take place without shelter, weather conditions can affect the construction programme. However, the extensive use of tilt-up in New Zealand and Canada indicates that simple measures such as proper use of weather forecasting and protective measures can be useful (e.g. polythene sheeting to protect wet concrete from rain). Panel finish is important; more elaborate architectural finishes require additional form materials to create rebates, patterns or textures. Plastic formliners can be used to introduce relief to plain tilt-up facades; an economic option is a single-use formliner used for small areas of decoration.[23] Where more decoration is needed, the panels can incorporate large-scale patterns, colour pigments and textures (Fig. 9). Exposed aggregate techniques are also common, but in many countries painted finishes appear the most popular for tilt-up (Fig. 10). This may be because painted finishes enable casting to be speedy and simple, as well as being flexible in the long term.

19. After sufficient curing, panels are lifted into position. Lifting day is a critical time for a tilt-up project. With good planning, experienced contractors can lift up to 50 panels in a working day, but the average lift time per panel is about 30 min. It is at this point when investment in good practice in design and construction planning pays off by a fast and safe lift. Panels are erected and braced into position and props remain in place until the superstructure is complete enough to provide any necessary support. Tilt-up panels are sometimes designed to cantilever from a strip footing; the resulting perimeter trench is filled later with an *in situ* stitch between slab and panel.

20. Other connections include those between adjacent tilt-up panels. Where these are

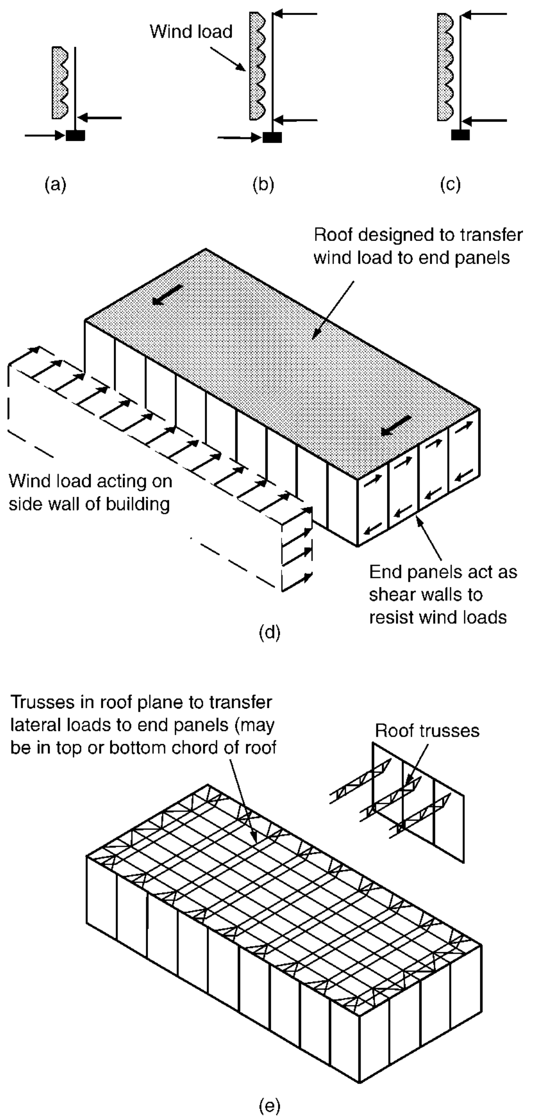

Fig. 8. Transverse-load resistance (courtesy Reinforced Concrete Council): (a) straight cantilever; (b) propped cantilever; (c) simply supported; (d) principle; (e) general arrangement (stability in case (a) is by straight-cantilever action; for cases (b) and (c) see (d) and (e))

Fig. 9. Hand-laid rock finish, Sacramento, California

required, they are designed to be ductile to allow movement, such as thermal movement and shrinkage, yet transmit any designed-for forces. The resulting joints most commonly employ a one-stage joint of foam backer rod and field-moulded joint sealant. However, in severe climatic conditions, a multiple-stage joint may be chosen; this uses a minimum of two lines of sealant. The dry baffle joints used in precast concrete construction are less typical for tilt-up. Connections between the tilt-up panel and roof structure are designed according to the type of roof specified, but in all cases should be designed and constructed to transfer lateral loads between the panels and roof.[24] Finishing procedures are often undertaken in parallel with other activities on site, and when the props are removed, only minor remedial (patching) work should be required.

21. Clearly, tilt-up construction is best suited to a procurement scenario where the design and construction teams can convene at the earliest opportunity. Indeed there seems to be a mutually dependent relationship between on-site processes and design activities which requires such an arrangement. For this reason, design–build has been referred to as the 'tailor-made' procurement route for tilt-up; it enables single-point responsibility, teamwork, reduced construction time and an early start on site.[25] However, there is doubt that design–build is the universal panacea, particularly in newer markets where pooling of expertise in the first instance may involve many firms or individuals. Recent trends towards 'partnering' may also be helpful for those wishing to use tilt-up. The key point is that the design and construction activities associated with tilt-up are linked closely and that this relationship facilitates good preplanning for efficient on-site activities.

22. As well as being renowned for constructional efficiency, tilt-up panels offer other benefits during their service life, including inherent fire resistance, 'free' passive cooling and enhanced acoustic performance, as described in the next section.

Performance issues

23. This section focuses on the long-term benefits related to the in-service performance of tilt-up. It should be noted that the buildings for which tilt-up is used typically do not currently have a very high performance specification. Industrial design is often more concerned with efficient planning than with the performance of the building envelope. Nevertheless, tilt-up concrete panels can offer added performance value in three particular aspects: fire protection, thermal capacity and acoustic insulation.

24. The fire resistance properties of tilt-up panels are similar to those of any solid concrete wall construction (see Table 1). This inherent advantage has made tilt-up popular with industrial clients requiring firewalls between high-value stocks. UK media attention on the fire performance of some metal sandwich panels after several fires in food-processing plants has also sparked interest in tilt-up, and a recent report demonstrated that tilt-up sandwich panels do not pose a similar risk, provided joints and service entry points are protected.[26]

Fig. 10. Painted finish, Watchtower offices, Co. Wicklow, Ireland

25. The manner in which tilt-up structures behave in fire has been the subject of some research; Australian guidance recommends that panels be designed to sag inwards in the event of a serious fire to avoid collapse.[27] In practice, panels are pulled inwards by sagging roof members, sometimes by as little as 50 mm, depending on the design of the roof–panel connection, and in general the behaviour of the tilt-up panels is little different from that of factory-precast concrete panels. Reports of fires[28] include an example in Phoenix, Arizona, where high temperatures caused only slight blistering on the internal surface of the panels.

26. Although the thermal resistance of concrete is low, tilt-up concrete can, when combined with insulation, offer good thermal

Table 1. Fire resistance of tilt-up panels

Fire rating: h	Minimum panel thickness: mm
0·5	100
1	120
1·5	140
2	160
3	200
4	240

properties. Insulation can be applied either to the internal/external faces of the tilt-up panel using proprietary systems, or through rigid insulation cast within two layers of concrete as a sandwich panel. Sandwich panels are more expensive, but have a very robust finish and offer very stable internal temperatures, which may be particularly appropriate for food processing, cold stores or clean-room facilities (Fig. 11). Manufacturers now offer predrilled insulation sheets for use with specialist tilt-up connectors (metal or plastic composite rods) which minimize thermal bridging between the two concrete leaves. Typically, a 75 mm layer of extruded polystyrene (EPS) combined with 125 mm and 75 mm concrete leaves will give a U value of 0·37 W/m^2 K, which is well within UK building regulation requirements. In very cold climates (e.g. Canada), insulation thicknesses of 100–150 mm are more common.[29] In countries with warm climates, tilt-up panels may be used without insulation.

27. Concrete regulates the internal temperature by slowing down heat transfer through the building envelope. This time lag is due to the concrete's high level of thermal mass, a characteristic that enables it to absorb, retain and later release large amounts of warmth or 'coolth'. The key to achieving this effect is ensuring that the internal face of the panel is exposed; in which case, the best compromise for temperate climates is insulated sandwich panels. These satisfy the thermal-insulation requirements of current UK building regulations, but also allow the natural thermal mass in the concrete to be utilized. In the US energy research[30] has demonstrated that sandwich panels with high thermal mass show improved U values when dynamic temperature effects are taken into account in calculations. Elsewhere, the market appeal of tilt-up in New Zealand[31] is said to have improved specifically because of the thermal advantages of sandwich panels.

28. Tilt-up panels have acoustic properties similar to those of other concrete panels, the performance of which is well documented. For all such walls, the mass law for sound reduction applies, where a doubling of mass improves the sound reduction index by 4 dB. The dense concrete wall panels provide good sound reduction values provided joints and openings are also detailed properly (Table 2). This performance advantage has been capitalized on in residential tilt-up buildings to prevent noise transmission between dwellings, and in industrial applications where it offers protection against sound transmission from machinery. With values of at least 50 dB or better, tilt-up wall panels offer significantly higher inherent sound reduction properties than conventional metal cladding, which, owing partly to its low mass, often provides less than 30 dB of sound reduction.[15]

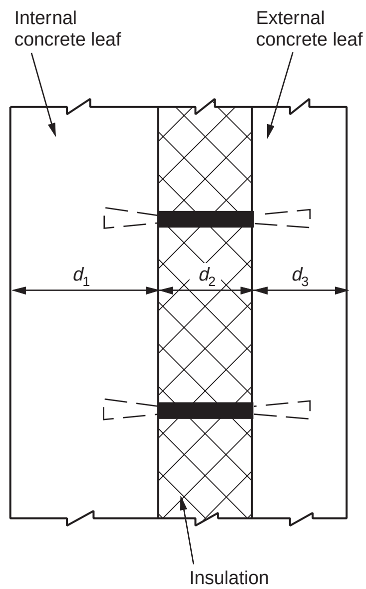

Fig. 11. Typical cross-section of a sandwich panel (courtesy Reinforced Concrete Council)

29. Tilt-up therefore offers the same inherent advantages in terms of thermal, acoustic and fire performance as any other type of solid concrete construction. However, when combined with the cost and programme benefits indicated in the following section, tilt-up can offer significant performance advantages over lightweight construction methods. The next section outlines research findings on the cost of tilt-up for the UK, including costs for firewalls and insulated sandwich panels.

The cost model for tilt-up

30. Take-up of tilt-up in the UK has been limited to date, but evidence from other countries indicates that it has been very successful in markets similar to the UK. From the previous sections it has been shown that the design principles are clear, that the construction process is well documented and that there are evident performance advantages. However, tilt-up must also be shown to be economic to construct if it is to succeed in the UK. For this reason, a set of predictive costs for tilt-up is presented. The findings of an attitudinal survey, noted in the following section, should also be taken into consideration.

31. The PhD research[12] on which this paper is based included the development of a cost model to predict likely construction costs for tilt-up in the UK. In accordance with accepted

Table 2. Sound insulation of tilt-up panels (for normal-weight concrete)

	Acoustic characteristics	
Panel thickness: mm	Weight: kg/m^2	Sound reduction index: dB
100	244	50·5
125	303	52
150	361	53·5

Table 3. Total building costs per m^2 GFA

Construction options (1–4: tilt-up; 5–8: conventional methods)	Building A, 2304 m^2, 6 m eaves: £	Building B, 4500 m^2, 8 m eaves: £	Building C, 9180 m^2, 10 m eaves: £	Building D, 18 090 m^2, 12 m eaves: £
1. Load-bearing tilt-up panels	360	324	319	292
2. Insulated sandwich panels	374	338	329	299
3. Decorated tilt-up panels	361	326	320	292
4. Tilt-up cladding panels	355	327	327	294
5. Built-up system cladding	342	320	321	288
6. Composite cladding panels	387	360	357	318
7. Aluminium cladding panels	421	391	384	339
8. Blockwork/built-up combination	354	328	327	292

definitions,[32] a cost model should be simple to use, yet able to perform complex tasks, and consist of a conceptual framework into which data is inputted, a set of assumptions which use the data to perform calculations and a set of results. To provide results to identify the cost effects of specifying tilt-up, the conceptual framework of the cost model was based on an elemental cost analysis (i.e. analysed in terms of building elements). The model was developed in collaboration with, and verified by, several UK and US companies, some of which had experience of using tilt-up (see the Acknowledgements section); this ensures the reliability and accuracy of the method and data. Furthermore, the number of items costed in each tilt-up analysis exceeded 100, which corresponds to a 92–93% mean level of accuracy.[33]

32. The cost model was based on a generic low-rise B1, or 'shed' type, structure, with a single-storey storage/production space fronted by a two-storey office block. This building type was selected because it is both the 'entry market' and the predominant end use for tilt-up construction in many other countries. For such buildings, tilt-up is said to offer a fast programme, tough, robust walls and the ability to support long span roofs (i.e. it can be used without portals). These are all advantages which can be appealing to industrial developers. A range of gross floor areas (approximately 2000 m^2–20 000 m^2 GFA) and internal clear heights (6 m–12 m) was selected on advice from property agents and by using benchmark designs from industrial developers. For all these designs, generic building specifications were developed, using UK Building Regulations and 'best practice' guidance from an advisory group of UK engineers, contractors, developers, quantity surveyors and manufacturers.

33. Structural design of the tilt-up panels was carried out in collaboration with engineers and tilt-up contractors. The model compared the costs of types of tilt-up panels with a range of conventional construction methods (i.e. metal-intensive and masonry solutions) for B1 buildings. The tilt-up options included load-bearing panels with a plain, painted finish, load-bearing panels with a decorative rebate, load-bearing insulated sandwich panels and simple, non-load-bearing cladding panels (combined with a portal frame). The range of conventional construction methods included built-up metal cladding systems, composite insulated metal panels, an aluminium cladding system and a blockwork/built-up metal cladding system combination.

34. The total model therefore encompassed 32 design and construction variations. Cost data for these were collated from public sources[34] and from contractors' own private databases of current building costs. In parallel with construction cost information, some key site-based costs (preliminaries[35]) were also covered by developing construction programmes for the 32 options in consultation with a contractor and an independent construction manager. A summary of the construction cost data produced by the model is given in Tables 3–5. (The index-linked cost point is January 1998 and the assumed location is outer London. Landfill tax, materials, labour, preliminaries and professional fees are included, but profit, variations and VAT are excluded.)

35. The results show load-bearing tilt-up panels to be broadly cost-competitive with other forms of conventional construction. Plain load-bearing panels are comparable with the most economical metal cladding system for the larger of the buildings costed, and tilt-up insulated sandwich panels are consistently cheaper than metal composite panels (see Table 3). On Building C, load-bearing tilt-up is actually £2/m^2 cheaper than the built-up cladding system (owing partly to a requirement for compartment firewalls, where tilt-up internal fire walls cost £36/m^2 per unit wall area compared with £72/m^2 for conventional drywall steel and plasterboard systems). The option of using tilt-up as a cladding panel with a steel portal frame as support is also economical and competes well with the blockwork/built-up system combination, which is popular for B1 buildings in the UK.

*Table 4. External-wall costs per m^2 wall area, including plant-based preliminaries**

Construction options (1–4: tilt-up; 5–8: conventional methods)	Building A: £	Building B: £	Building C: £	Building D: £
1. Load-bearing tilt-up panels	49	50	54	57
2. Insulated sandwich panels	62	65	69	72
3. Decorated tilt-up panels	51	52	56	59
4. Tilt-up cladding panels	39	39	41	42
5. Built-up system cladding	36	36	36	36
6. Composite cladding panels	104	104	104	104
7. Aluminium cladding panels	155	155	155	155
8. Blockwork/built-up combination	48	45	43	43

*Tilt-up costs may be up to 10% less if bracing and lifting equipment costs are divided between more than one project, or are hired rather than purchased. Conventional cladding costs have been fixed for reasons of comparability, and do not include steelwork costs.

*Table 5. Times from mobilization to completion using published lead times: weeks**

	Building A	Building B	Building C	Building D
1. Load-bearing tilt-up panels	17	23	29	33
2. Insulated sandwich panels	18	24	31	35
3. Metal cladding panels	13	19	29	33

*Data based on published lead times; overseas projects suggest these may be considerably reduced on tilt-up projects, for example a two week reduction could result in at least a 1% saving in total building costs.

36. As the floor area increases, the wall : floor ratio changes, and for the largest building (D), a breakdown of superstructure costs shows that the cost of the roof exceeds the cost of the external walls, thereby making the walls a less critical element. The situation is similar for substructure costs, which are comparable for both tilt-up and conventional construction options, but as the floor area increases the ground slab becomes a dominant cost element. Furthermore, extrapolation of the costs per square metre into cost per unit volume (£/m^3) indicates that building height is a more important variable than floor area. Indeed, the cost of erecting tilt-up panels does increase for taller buildings, owing to the added weight of the panels and an associated increase in lifting costs, but a doubling in height from 6 m to 12 m incurs only approximately a 16% increase in external-wall costs.

37. Considering the cost per unit wall area in more detail, the tilt-up options are affected by panel design, lifting equipment, insulation and finishing methods. The relative proportions of the materials used vary according to panel design. The concrete content varies from 27 to 40% of the panel costs (as thickness increases with height), and for the insulated sandwich panels the cost of the two layers of concrete is actually outweighed by the cost of the insulation system and connectors specified. Weld plates and connections between the tilt-up panels consistently account for about 8% of the panel costs, and formwork accounts for about 4%. Most importantly, Table 4 shows that the tilt-up options cost in the range £39–72/m^2, and are therefore competitive with a very wide range of other cladding options available in the UK. Additional finishing to the tilt-up panels need add only a few per cent to the costs shown.

38. In terms of the construction programme, published lead times have been used, and normal site conditions have been assumed. Table 5 shows that these assumptions produce construction times of 13–35 weeks, and that tilt-up becomes very competitive on buildings C and D where the plain load-bearing tilt-up option can be erected in the same time as a conventional metal cladding panel construction. Insulated sandwich panels remain consistently 1–2 weeks behind the fastest programmes owing simply to casting and curing the additional layer of concrete. However, on complex buildings such as cold stores, insulated tilt-up panels can offer 4–6 week savings in the programme compared with specialist blockwork/metal cladding systems. On the basis of these construction times, the model included some key preliminaries (quality and standards, management and staff, site accommodation, services and facilities, mechanical plant and temporary works), which constitute 5–7% of the conventional-construction option costs, and 7–13% of the tilt-up-construction option costs. Over time, the cost of preliminaries for tilt-up is likely to reduce. For example, those contractors which invest in lifting and temporary-bracing equipment and use it over a series of projects will be able to offer prices significantly reduced from those shown in Table 4, which assumes a 100% purchase cost for these items.

39. The costs presented indicate that tilt-up can be competitive in the B1 'shed' market, offering immediate savings over some conventional metal cladding construction methods as well as 'added benefits'. There is a clear relationship between good practice in design and the resultant construction costs, and therefore the cost model has shown that an understanding of design principles, the construction process and potential performance benefits can result in an economical tilt-up building with both short- and long-term benefits.

Perceptions of tilt-up

40. A series of in-depth personal interviews were carried out with a range of construction industry professionals in the UK and USA as part of the PhD research project noted previously. The aim of this stage of the research was to focus on issues perceived to be important to, or influential on, the acceptance and take-up of tilt-up in the UK. This included issues that, by their nature, were broader and more complex than the cost, performance and design considerations analysed earlier in the research. Interviewees were selected on the basis of their having both a considerable experience of the UK construction industry and having at least a basic knowledge of tilt-up either in the UK or elsewhere. Analysis of the interviews revealed that several issues relating to the use of tilt-up were of concern to the participants. In particular, the participants noted some key considerations that they felt could impede the take-up of tilt-up in the UK; these are outlined below.

41. Many interviewees considered that tilt-up would be less suitable for the UK simply because they thought it required a large, free site to cast the slab and panels and that the UK lacked such extensive plots for building. While there is some logic to this point, in practice it is not a major issue, because tilt-up can be used on tight sites using 'stack' casting. Some interviewees considered that tilt-up was most likely to be accepted in the UK if used as part of a 'hybrid' construction with a conventional outer leaf of brickwork, for example. They noted that the architectural styles favoured by other countries were not strictly compatible with those of the UK, and that effort could be made to develop a 'home-grown' solution for walls. However, trends in industrial building refute this claim; very few shed-type buildings use masonry facing materials. Where such finishes are required, tilt-up panels can be combined with a brickwork outer skin.

42. As noted previously, potential performance benefits relating to fire and to acoustic and fire insulation were also highlighted by the interviewees as key advantages of concrete construction, not simply tilt-up panels. Several people considered that the most suitable procurement routes for tilt-up in the UK would be those using some form of 'team' approach, i.e. design–build and partnering. They noted that projects using more competitive forms of tendering might hinder the preplanning stages which are characteristic of a tilt-up project.

43. Several interviewees spoke about a cultural resistance to change on many levels in the construction industry. Some said that there was a very broad-brush feeling against new (or less well known) techniques, but others said there can be resistance to technologies simply because UK practitioners believe that these will involve a fundamental change or shift in the ways they work. Further to this general reluctance to change, there was also evidence that the interviewees held rather fixed or stereotyped opinions about concrete as a material, which of course would affect the use of tilt-up. Some thought there was a major stigma surrounding concrete building 'systems' and precast panelized systems in general. Although this wider cultural context needs to be considered, tilt-up is used principally for low-rise buildings and is best thought of as a construction method rather than a building 'system'.

44. Fifty per cent of the interviewees expressed concern about the impact of weather conditions on tilt-up construction in both the short and the long term; first, that the inclement UK weather would adversely affect outdoor casting of the slab and panels, and second that weathering of the panels would occur once in place. However, the use of tilt-up in wetter and colder countries such as Canada and New Zealand suggests this perceived problem may not be as significant as people believe.

45. So, there is also a group of issues specific to tilt-up that appears to be impeding the use of this technique, and probably other forms of concrete construction. These, when combined with other influential factors such as cost, performance and design considerations seem to produce a set of 'roadblocks' to change. A greater awareness of the potential offered by tilt-up may ensure such roadblocks are only temporary.

Conclusions

46. This paper has outlined the development of tilt-up concrete construction from its origins as an experimental technique to its current status as a widely accepted method of building for many types of structure, in many countries. The refinement of the structural and architectural design principles of tilt-up has enhanced its profile within the construction industry. The combination of published design and construction manuals and computer design programs has accelerated take-up of the technique. The key to successful tilt-up construction appears to be a close working relationship between those involved with design and those

responsible for construction. Certain procurement routes seem to favour this scenario, and contractor-led arrangements are common in the tilt-up industry.

47. Overseas research and practice provide evidence that the concrete panels have inherent long-term benefits in terms of thermal, acoustic and fire performance, which can prove attractive when considered in combination with the short-term cost advantages. The potential cost savings offered by tilt-up can be maximized by efficient structural design, close collaboration between all parties and well-managed construction sites. This paper has identified some of the specific advantages of tilt-up and referred to some of the generic benefits of concrete construction. It has also illustrated the need for designers to be aware of the inherent characteristics of the technique in order to maximize these potential benefits. There is evidence that tilt-up could be appropriate to, and useful for, the UK construction industry; current unofficial estimates put the potential market for tilt-up in the UK at 700 000 m^3 of concrete per annum, which equates to over 2400 buildings. If this level was attained, then tilt-up could lead a concrete wall panel renaissance in the UK.

48. Although this simple construction method can offer fast, economical buildings, to date its use has been somewhat limited in the UK compared with other countries such as the USA, Australia and Canada. The PhD research on which this paper is based suggests this is due not only to a lack of UK-specific design, construction and cost information, but also to a cultural resistance to change within the construction industry. In combination, these factors have hampered take-up of the technique to date. Certainly, the availability of reliable cost and programming data on tilt-up which was specific to the UK could positively influence take-up of the technique, but in the words of one interviewee the combination of 'what it costs and what it looks like' is often of greater importance.

49. The difficulty faced by tilt-up in the UK is that there is a genuine stigma and scepticism surrounding exposed concrete, and a culture has developed which resists the idea that any non-conventional construction methods could be more visually acceptable and more cost-competitive than conventional construction or offer significant extra benefits to users. However, there are solutions to many of the perceived problems, and it is these perceptions that need to be addressed by the raising of people's awareness of the possibilities offered by tilt-up construction.

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