Condensation risk – impact of improvements to Part L and robust details on Part C

Final report: BD2414

Condensation risk – impact of improvements to Part L and robust details on Part C

Final report: BD2414

Tadj Oreszczyn, Dejan Mumovic, Mike Davies and Ian Ridley
University College London
Malcolm Bell, Melanie Smith, Dominic Miles-Shenton
Leeds Metropolitan University

Department for Communities and Local Government

This research was commissioned by the previous government. The views and analysis expressed in this report are those of the authors and do not necessarily reflect those of the Department for Communities and Local Government. This document is being published in the interests of transparency.

Department for Communities and Local Government
Eland House
Bressenden Place
London
SW1E 5DU
Telephone: 030 3444 0000
Website: www.communities.gov.uk

If you require this publication in an alternative format please email alternativeformats@communities.gsi.gov.uk

DCLG Publications
Tel: 030 0123 1124
Fax: 030 0123 1125

Email: product@communities.gsi.gov.uk
Online via the website: www.communities.gov.uk

ISBN: 978 1 4098 2882 2

Contents

	Page
Executive Summary	**4**
Introduction	**7**
Part 1: Initial workshop and site selection	**7**
Part 2: Fieldwork	**9**
Part 3: Condensation risk: comparison of 'simple' and 'complex' models	**11**
Part 4: An evaluation of the hygrothermal performance of 'standard' and 'as built' construction details	**13**
Part 5: Investigation of the potential impact of selected factors on condensation risk in robust details and in typical UK dwellings	**21**
Workshop (Milestone 12)	**23**
Suggestions for further work	**24**
Dissemination	**25**
Discussion and conclusions	**25**
References	**26**
List of appendices	**27**
Appendices	

Executive summary

1. This report summarises the main findings of the project 'Impacts of Improvements to Part L and Robust Construction Details (RCD) on Part C'. The work consisted of a fieldwork element, undertaken by Leeds Metropolitan University and a modelling element carried out by University College London. Details of the work programme are contained in Appendix 1. The fieldwork consisted of the analysis of design material and site surveys from 16 housing developments constructed to Part L 2002 and adopting the Robust Construction Detail route to compliance. The modelling element of the project sought to identify the extent to which the 'as built' details give rise to a significantly increased condensation risk as compared to the relevant 'standard' robust construction details, as defined in the guidance. In addition to assessing 'as built' performance, the modelling phase of the project has investigated the suitability of the relevant calculation methods used to assess the risk of surface and interstitial condensation and mould growth. This report draws together the important conclusions from the project which has previously been presented in several very detailed interim reports and also for the first time presents the results of a workshop where these results were discussed to obtain industry feedback. The overall conclusions, future work and dissemination plans are also presented.

<u>FIELDWORK</u>

2. The fieldwork element of the project began with an industry workshop, which was designed to develop an understanding of the application of RCDs from the point of view of industry and to develop criteria for site selection. The workshop was held in December 2003, attended by 22 professionals and academics drawn from private and social housing developers, building control bodies and suppliers and manufacturers and the participating universities. A further 5 invitees (late withdrawals) were asked to comment on a draft workshop report.

3. Delegates recognised the value of a robust detail approach but raised concerns about their application. In the context of design, concerns were raised about how designers would translate the material into practical details, the buildability of some recommended designs and the lack of material on design principles. There was a broad view that however well designed, many of the problems related to the reality of construction. The lack of knowledge and understanding among designers, site personnel and building control was considered to be an important barrier to improved performance. Apart from the obvious need for training, many of the difficulties were thought to relate to the rather diffuse nature of the responsibilities involved throughout the design, construction and checking process.

4. Site selection criteria focused on providing as broad a range of constructions and locations as possible. Sixteen developments were included in the study (one more than originally proposed) with locations in the NE, NW, SE and SW of England. Constructions included Masonry Cavity (full and partial fill), Timber Frame and Light Steel Frame and covered both private and social housing developers.

5. Following the initial workshop, the design and construction of the selected developments was surveyed over a 7 month period from March to September 2004. Some 1300 photographs and other graphical data together with site notes were logged into a database and analysed. The analysis revealed that:

- The level of knowledge about RCDs was low, particularly at the site level.
- The incorporation of RCDs into drawings was extremely varied ranging from small scale general arrangement drawings with a note requiring RCDs "to be complied with" to large scale drawings of relevant details available on site. Even where large scale drawings were available there was little evidence of their effective use by operatives.
- Construction problems were widespread and observed across all areas and types of construction. Problems related to the placement of insulation, the lack of adequate air and vapour control layers, detailing around high conductivity elements such as steel beams and a failure to deal adequately with services penetrations of external elements. Most of the observed problems were such as to increase the risk of thermal bridging, bulk air movement into and through the structure and associated condensation.

6. Developer response to the fieldwork findings placed considerable stress on the need for formal confirmation or accreditation of the detailing knowledge and that the successful transfer of that knowledge

to the site operative is imperative, warning that if this is not done effectively, there would be little point in improving the range and sophistication of a robust detail system.

MODELLING

7. Computer modelling was undertaken during the project for the following two reasons:

- To determine if the standard (‘simple’)methods of modelling the hygrothermal performance of details differ significantly in their prediction of interstitial condensation and mould growth from more complex calculation methods. Inter-model comparisons of a set of robust details were undertaken using ‘simple’ and ‘complex’ simulation packages.
- To identify the risk of interstitial condensation and mould growth as a result of details being constructed differently from that specified in the RCD document. Based on the fieldwork results 19 cases were selected for hygrothermal modelling under standard conditions so that the differences in performance between the details as illustrated in the RCD document (the ‘standard’ version) and as the ‘as built’ version could be explored.

8. The results of the inter model comparison suggest that the simple (current) simulation methods, as specified in the relevant Standard (BS EN ISO 13788: 2002), give good agreement with more complex transient and multi-dimensional calculation methods provided that either driving rain is not an issue or that the internal conditions are not subject to severe transients. When the fabric is subject to these conditions, the complex models differ significantly from the simple methods.

9. The modelling revealed that whereas no surface condensation risk is predicted for the ‘standard’ RCDs, 10 out of 12 of the ‘as built’ details failed to meet the Standard requirements regarding mould growth.

10. The ‘as built’ details satisfied the drying out requirements given in the Standard regarding interstitial condensation. However, in 4 out of 7 cases some condensation is predicted at times when none is predicted for the ‘standard’ robust details. The risk of degradation of building materials and the deterioration of thermal performance as a consequence of the calculated maximum amount of moisture should be considered.

11. A nomogram has been developed using Condensation Targeter to quantify the effect of workmanship on the thermal performance of both ‘standard’ and ‘as built’ RCDs. Note that for the vapour pressure excess predicted by the Condensation Targeter and given in the nomogram, two out of the four ‘most at risk’ ‘as built’ construction details would fail the standard requirements related to condensation risk. If ‘high’ moisture production was assumed, i.e. ‘wet’ occupancy, three out of the four details would fail the requirements concerning condensation risk.

12. It is evident that the influence of workmanship on moisture performance exists, and can have a significant effect on the hygrothermal performance of ‘as built’ robust details.

13. Furthermore, it appears that the potential impact of the occupier on moisture generation can be significant. Sensitivity analysis for selected ‘as built’ construction details has also been undertaken and highlighted some important issues.

14. For many of the RCDs analysed in this report the ‘incorrect’ construction of these details requires the relative humidity (RH) within the dwellings to be maintained significantly lower to avoid mould growth or interstitial condensation than if they had been constructed ‘correctly’. For example, for a typical RCD, to achieve the required reduction in relative humidity to avoid mould growth on the ‘as built’ detail compared to the ‘standard’ detail would require an increase in air change rate of approximately 30% - from say a nominal 0.5 ach to 0.65 ach. The energy implications of such increased ventilation will be significant. In practice these defects have probably not resulted in problems or the necessity for increased ventilation because of the relatively leaky nature of properties currently constructed. However, as the regulations tighten up the air infiltration rate of properties this is likely to become a more critical issue.

15. The work so far undertaken offers the unique opportunity to monitor the real performance of robust details as constructed which would both provide critical evidence to support the theoretical modelling which underpins the RCDs and also provide visual images to disseminate the impact of poor on-site construction. A brief description of a possible follow on project is described.

16. The results of the research have been discussed with the construction industry. Feedback from these discussions suggests that there is nothing particularly anomalous or atypical in the results of the project or the conclusions that have been drawn.

17. Dissemination of the results is underway through the publication of 3 academic journal articles including a special edition of 'Structural Survey'. It is also recommended that a dissemination strategy for the non-academic audience is developed.

Introduction

18. The most recent changes to Part L came into effect in April 2002 and introduced lower U values. In support of Part L, the guidance on reducing thermal bridging has been improved and new guidance has been produced on reducing unwanted air leakage.

19. The objectives of this study were as follows (for full details of the project proposal see Appendix 1):

- to carry out a theoretical assessment of condensation risks for Robust Construction Details (RCDs) using the current simpler calculation methods and the more complex and realistic method being developed by CEN. This objective requires two separate activities a) the theoretical assessment of condensation risk of 'robust details' and b) a comparison between simple calculation methods and the more "realistic" complex methods.
- to investigate actual construction details on site and to estimate the possible influence of workmanship on the moisture performance of RCDs. In responding to this objective, the field work element focused on emerging practice in the use of domestic RCDs following the 2002 revision of Part L. The objective was to establish both design and construction practice in the application of RCDs with particular reference to the impact of practice on condensation risk.
- to investigate the potential impact of the occupier on moisture generation in housing in particular e.g. the effect of placement of furniture against external walls, generating large quantities of water vapour etc..
- to reach a conclusion as to whether the current guidance referenced in Part C is sufficient to ensure that condensation problems are unlikely to occur in practice for new buildings.
- to provide recommendations arising from the conclusions as to any further guidance that may be required.

20. The detail of the research has been presented in previous interim reports - the key reports are attached as appendices to this report.

21. The work presented in this report is divided in the following subsections:

- Part 1. 'Initial workshop and site selection'
- Part 2. 'Fieldwork'
- Part 3 'Condensation risk: comparison of 'simple and 'complex' models'
- Part 4 'An evaluation of the hygrothermal performance of the 'standard' and 'as built' construction details'
- Part 5. 'Investigation of the potential impact of selected factors on condensation risk in robust details and in typical UK dwellings'

Part 1: Initial workshop and site selection

22. In order to provide a starting point for the fieldwork element of the study, an initial workshop was held in December 2003 with the twin objectives of exploring practical experience in applying Part L Robust Construction Details (RCDs - DEFRA and DTLR, 2001) and establishing site selection criteria for the 15 sites to be used in the study. Some 22 people participated in the workshops with a further 5 (late withdrawals) invited to comment. The participants included private sector housing developers, social housing developers, representatives from the timber frame and steel frame industries, building control officers & approved inspectors, and representatives from industry material suppliers & trade associations. In addition workshop participants were asked to comment on the site data collection agreement and protocols developed by the research team. A full report on the workshop is presented in Appendix 2.

23. It was recognised that, since the need to adopt RCDs as a route to compliance with Part L was relatively recent, practical experience of using them in design and construction was limited and that the industry was still learning how to makes effective use of the approach. Despite the acknowledged

limitations of view there was general support for the principle of adopting robust details as a means of improving detail design and demonstrating Part L compliance but this was tempered by a number of concerns about the material in the document (its range and depth) and the likelihood that well designed details would be realised on site. The following key concerns emerged:

- The lack of explanation of the principles upon which each detail was based, together with a lack of performance data made it difficult for designers to adapt, modify and extend details to suit a particular scheme. It was noted also that the document was far from comprehensive in its coverage and that without a firm understanding of the design principles many designs will fail to achieve the required performance.

- The construction phase was seen as potentially the most problematic area because of the lack of understanding, at all levels, of the principles upon which the details were based and of the consequences of incorrect application. This was coupled with concerns about the buildability of some details, a concern that suggested a need for more attention to be given to the standardisation not only of details but also the range and type of preformed components that could overcome some of the buildability problems.

- The process of ensuring that details were designed and constructed in accordance with the requirements of the RCD document was thought to be rather diffuse with a number of different people and organisations involved from designer to site staff, operatives and building control. It was felt that the uncertainties inherent in the system often lead to avoidance of responsibility and a failure of the system as a whole to identify the causes of procedural as well as technical problems.

- Many at the workshop identified a need for training that would enable the successful application of details both in design and construction.

24. Discussion, at the workshop, relating to site selection concluded that site selection should, as far as possible adopt the following broad criteria:

- Sites must to be designed and constructed under approvals issued in accordance with the 2002 edition of Building Regulation Part L1 and to adopt Robust Details as the compliance route for thermal bridging and airtightness.

- The principle forms of dwelling construction (Partial & Full Fill Cavity Masonry, Timber Frame, and Light Steel Frame) should be represented with the vast majority being of either masonry or timber frame.

- In order to ensure that observation cover as broad a range of details as possible sites should be selected with dwellings at all stages of construction, from ground floor to completion of the superstructure and finishes.

- Although it was understood that the number of sites that could be included in the study (15) would not be large enough to provide a representative sample of dwelling construction, it was considered important to include sites from the principal geographical regions (SE, SW, NE, & NW) across England.

- Developments should consist of a mix of large and smaller developers and cover both the social housing and private sector.

Selected sites and site surveys

25. Following the workshop, over 20 housing developments were identified yielding 16 sites suitable for data collection. Table 1 sets out the characteristics of the selected sites and indicates the number of surveys undertaken; details of the characteristics of each site and surveys undertaken are set out in the fieldwork report in Appendix 9.

Table 1: Characteristics of study sites

Characteristic	Description
Location – number of sites by region	North East – 7 sites North West – 5 sites South East – 2 sites South West – 2 sites
Type of Developer	Social housing developments – 5 Sites Private sector developments – 11 sites
Type of construction	Full-fill masonry – 2 sites Partial-fill masonry – 8 sites Timber frame – 5 sites Steel frame – 2 sites
Construction observations undertaken	20 site visits were undertaken. Most sites were visited only once but 3 sites received more than one visit in order to capture as wide a range of construction as possible. The following stages were observed: Ground floor slab and external walls – all 16 sites Intermediate floors, roof and internal partitions – 12 sites Internal finishes to completion – 8 sites

Part 2: Fieldwork

26. The fieldwork phase of the project consisted of an analysis of both design drawings and site observations for the developments identified after the initial workshop. A design and construction database was set up for each site and provided the principal recording mechanism for all design and site data. The database contains written descriptions of construction and site observations as well as some 1300 graphical items including photographs, scanned images from paper drawings, electronic drawing files (AutoCAD and dxf files) and site sketches. Sets of design drawings on paper or in electronic format were received from thirteen of the developers and a desktop study of these was made. The availability of the drawings on site was also assessed for each of these sites. For the remaining three sites, as no plans were received from the developers, the design details available on the sites were inspected at the time of the site visits, and design information taken from these as appropriate. Details of the fieldwork methodology and findings are contained in the fieldwork report provided in Appendix 9.

Key fieldwork findings

27. In analysing the results of the design assessments and site surveys we have sought to look at the data as symptomatic of the more general issues and problems that the house building industry, its support network and its regulators need to understand and address. Although, in a study of this nature it is easy to dwell on the specific instances of defective design and construction it is important to place them in perspective and to look beyond the specific observations and to avoid classifying them simply as "errors, defects or mistakes". In our view the observations of detailed design and construction, like many problems in the management of quality are ones of the system as a whole not of individual or developer culpability.

28. The fieldwork revealed a general lack of understanding of the detail design issues and the application of RCDs. Although the study does not claim to provide a representative sample[1] an attempt was made to assess whether the defects observed were isolated instances or reasonably typical. Some 20 classes of problem were identified and their prevalence assessed. The analysis indicated that 16 of

[1] The study was designed as a qualitative assessment of the nature of the detailing issues not a random sample of construction detailing defects.

the 20 types of defect were observed on at least half the potential number of sites[2] visited, indicating that most of the problems identified were broadly typical on the sites surveyed. The final report (see Appendix 9) identifies the following as the key issues to emerge:

- Knowledge and understanding relating to Robust Details and the principles of thermal bridging and airtightness they seek to embody is generally low. This is manifested in both design and at all levels of site operation. In almost all sites visited even the very existence of Part L RCDs was unknown. Where staff had heard of robust details this was in relation to Part E not Part L.
- The approach to design detailing was extremely varied. We observed a significant number of cases where detail design was often worked out on site and even when detail drawings were available they were not always clearly communicated to the person engaged in construction work. The lack of well communicated design information not only increases the likelihood of errors but also fails to take advantage of the training implicit in a well designed and communicated detail.
- The technical problems observed related, in the main, to ill fitting insulation both within an element and at junctions, a lack of attention to the continuity of vapour control and air barriers, a failure to recognise the significance of an identified air barrier, little understanding of thermal bridging problems, particularly when detailing around structural steel work and a general lack of understanding of the importance of detail design for thermal and condensation performance. In general, the salience of thermal bridging and air/vapour control in the minds of designer and constructor alike would appear to be low, to the point where many of the defects are considered to be very minor and of little significance.
- There is much to be done to improve the way RCDs are understood. The problems lie with the document itself and the extent to which the industry as a whole has sought to ensure that they are fully applied. Improvements are required in the document and the training that is required to ensure effective application.

29. Developer comments were sought on a draft of the fieldwork report. The comments received acknowledged that the report's observations identified recurring problem areas and pointed out the importance of education and training.

> *"You have successfully exposed the recurring problem areas faced by the industry and recognised the basic need for education and training on site. Without greater knowledge at ground level a ratcheting up of robustness in design detailing will never achieve its aims." (developer comment)*

30. Throughout the feedback there was considerable stress on the need for formal confirmation or accreditation of the detailing knowledge and that, as illustrated in the quotation above, the successful transfer of that knowledge to the site operative is imperative, warning that if this is not done effectively, there would be little point in improving the range and sophistication of a robust detail system.

31. The detailed findings of the field work were used to identify a sample of details to be subjected to hygrothermal modelling so as to establish the impact of actual construction on performance. To this end some 7 areas of detailing, yielding 19 individual cases, were selected using a balanced set of the following criteria:

- The prevalence of problems with the range of details studied,
- The extent to which problems observed related to more than one construction type,
- The inclusion of all the major junctions where design and construction problems were observed
- The inclusion of all forms of construction investigated as part of the study.

32. The results of the modelling exercise are summarised in Part 4 of this report and its associated appendix.

[2] In this context, potential, is defined as the number of sites on which a particular problem could have been observed, taking into account the stage of construction at the time of site visits as well as construction type. For example, if the problem were one relating to the first floor junction in timber frame construction, the potential was taken to be equal to the total number of timber frame sites that had reached first floor stage at the time of the site visits.

Part 3: Condensation risk: comparison of ‘simple’ and ‘complex’ models

33. This section of the report summarises the findings of comparing the predicted interstitial condensation and surface relative humidity using ‘simple’ (currently standard) calculations with more complex calculations which are now viable. The aim of this work is to determine what, if any, difference there is in the predictions with the more complex and when, if at all, it would be appropriate to undertake the more complex calculations. The key reports which provide the detail to support the summary presented in this section are included as Appendix 3 and 6 in this report.

34. The calculation methods, currently used in the UK to assess the risk of surface and interstitial condensation and mould growth, are specified in the following standard – BS EN ISO 13788: 2002: “Hygrothermal performance of building components and building elements – Internal surface temperature to avoid critical surface humidity and interstitial condensation methods”.

35. This section quantifies the difference in modelled surface and interstitial relative humidity (RH) for a number of typical RCDs (as illustrated in DEFRA and DTLR, 2001) using both simple steady state and complex transient models and therefore provides a quantitative indication of the types of errors which simple steady state modelling may introduce.

36. To assess the risk of surface condensation and mould growth using the simple steady-state method of calculation defined in the BS EN ISO 13788: 2002, the thermal analysis software TRISCO was used. Quality assurance was undertaken to test the performance of the tool as required for ‘high precision calculation methods’ according to Annex A of BS EN ISO 10211-1:1996 (EN ISO 10211-1:1995).

37. Transient analyses were undertaken using VOLTRA, as developed by Physibel, was used. VOLTRA is a transient version of TRISCO, the software used for the steady-state method – the two models are otherwise identical.

38. To assess the risk of interstitial condensation and mould growth two methods were used: (1) the Glaser method, commonly used to simulate vapour diffusion and condensation in building envelopes, as prescribed by BS EN ISO 13788 and (2) a more advanced calculation model based on transient moisture and heat transport through walls. Quality assurance was also undertaken to assess the performance of the software which incorporates the Glaser method, GLASTA, as required by the Standard with the test reference cases modelled and the relevant requirements met. For the more ‘advanced’ model the transient heat and moisture transport model WUFI was used as developed by IBP.

39. The RCDs selected for detailed analysis are those which have been identified as being particularly prone to difficulties in construction on site. Analysis of the impact of possible defects in construction is presented in Part 4 of this report.

40. In the case of surface condensation, significant differences are apparent between the predictions of the simple and complex methods for the particular boundary conditions applied to all RCDs modelled. The complex method tends to predict several hours above 80% RH (the point at which surface mould growth may become problematic, see Figure 1) at several locations on the internal surface of the robust details, mostly corners and lower areas of external walls and doors, whilst the simple method tends to predict that surface RH values are all significantly below 80%.

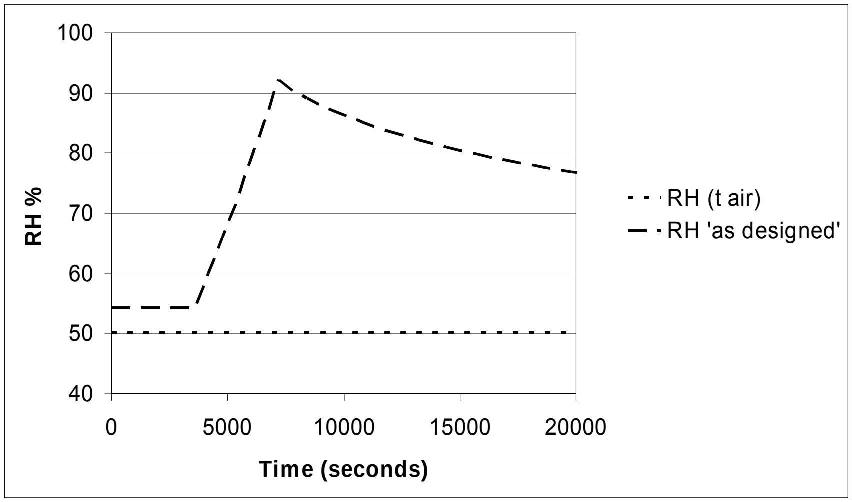


Figure 1. Predicted surface RH for a ‘standard’ RCD.

41. The effect of thermal mass on the assessment of mould growth using the complex calculation methods cannot be neglected, as the period in which RH remains above the threshold value of 80% in the case of ‘heavy weight’ construction is significantly higher than in the case of the ‘light weight’ construction.

42. In the case of interstitial condensation it was shown that the two calculation methods can provide different results in the prediction of risk of interstitial condensation, when driving rain is considered in the complex method. In the case of interstitial condensation, when driving rain is included in the complex method, significant moisture accumulation is predicted in the external brickwork layer and often in the air cavity (see Figure 2). Driving rain can not be considered in the simple interstitial method.

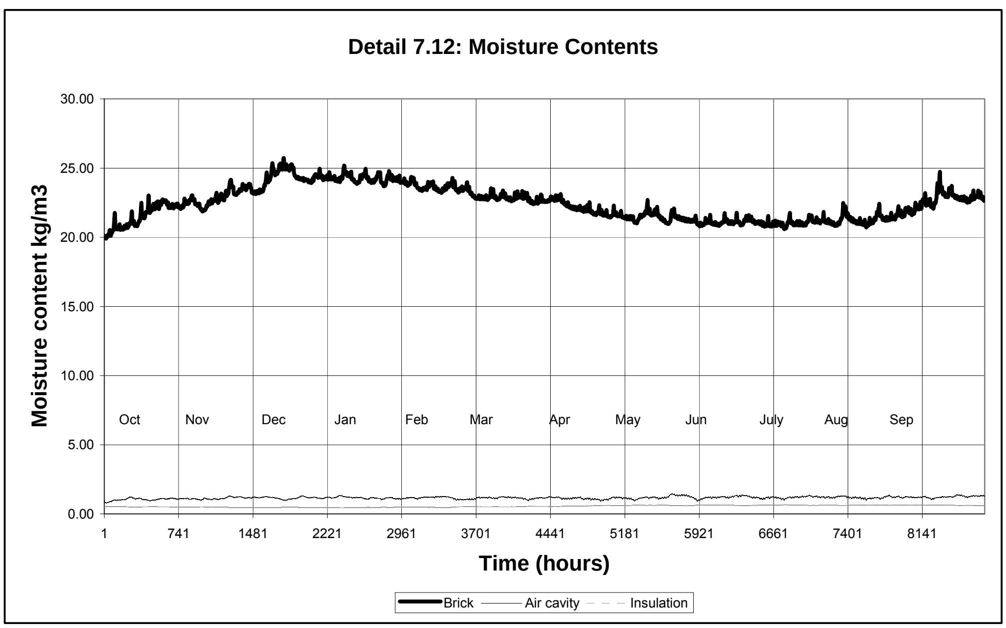


Figure 2. Moisture content predicted when driving rain is considered (RCD 4.19)

43. To summarise, for the RCDs modelled, simple (current) models give good agreement with more complex models provided that either driving rain is not an issue or that the internal conditions are not subject to severe transients. When the fabric is subject to these conditions, the complex models significantly differ from the simple models.

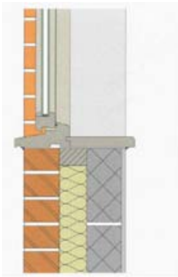
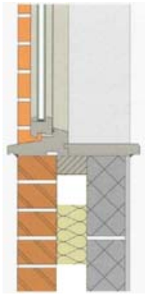
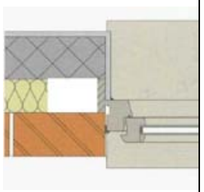
Part 4: An evaluation of the hygrothermal performance of ‘standard’ and ‘as built’ construction details

44. Accurate assessment of both surface and interstitial condensation risk at the design stage of buildings is of great importance – not just to minimise the damaging effects moisture can cause to building envelopes, but also to contribute to the provision of adequate indoor air quality. Clear evidence has been provided earlier in this report that the reality, both in translating the available guidance into a specific design and in construction on site is often rather different from the ‘ideal’. In this part of the report the results of both the surface and interstitial condensation risk simulation of ‘as designed’ and ‘as built’ RCDs are presented and discussed. The detailed reports specifying all assumptions etc are included in appendices 10 and 11.

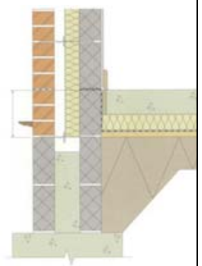
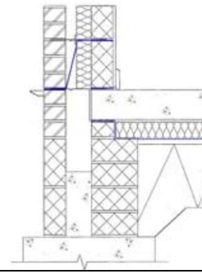
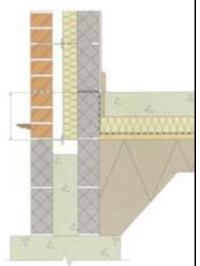
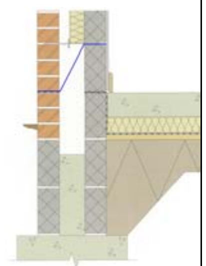
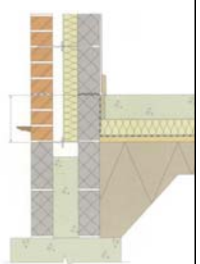
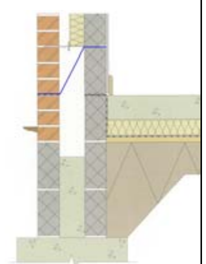
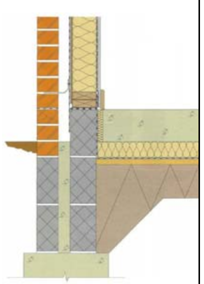
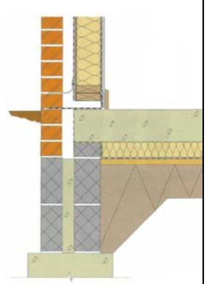
45. A set of nineteen different cases have been assessed for both surface and interstitial condensation risk. For a detailed description of the selected RCDs see Table 2. Note the use of the term ‘TDR’ in the table. BS5250 recommends that “A surface temperature factor of not less than 0.75 is considered to be sufficient to avoid mould growth, given the range of conditions in UK buildings and the UK climate”. Thus to avoid mould growth a TDR of less than 0.25 is required - cases with a TDR greater than 0.25 are highlighted.

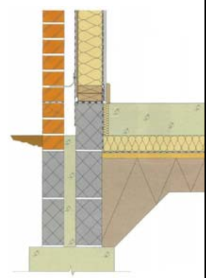
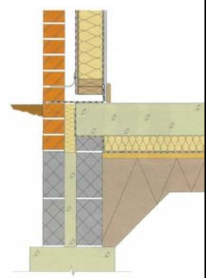
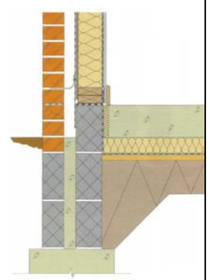
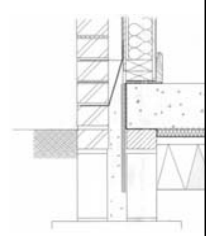
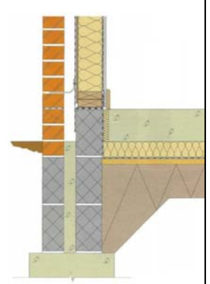
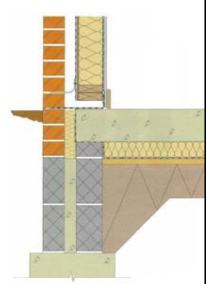
46. To assess the risk of both surface and interstitial condensation the simple steady-state method of calculation defined in the BS EN ISO 13788 was used.

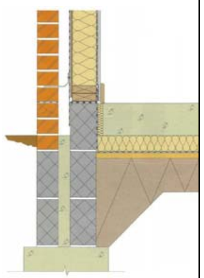
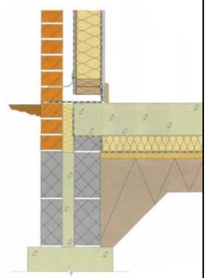
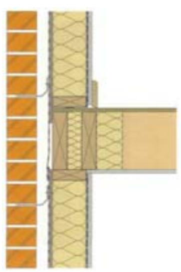
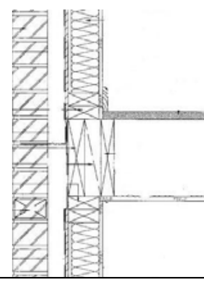
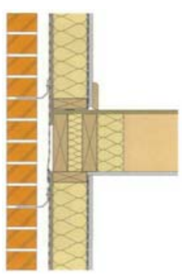
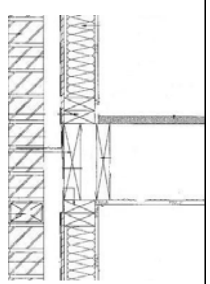
Table 2. RCDs assessed for both surface and interstitial condensation risk.

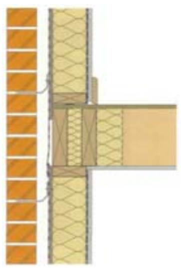
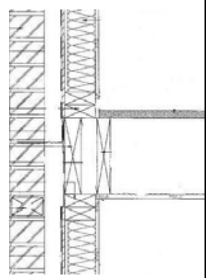
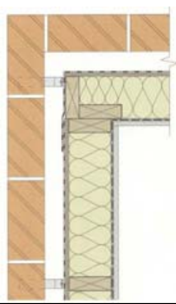
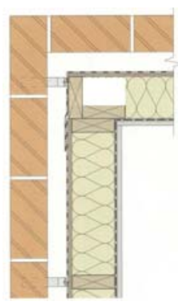
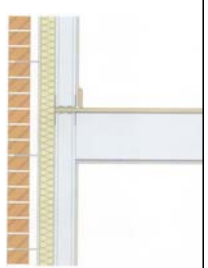
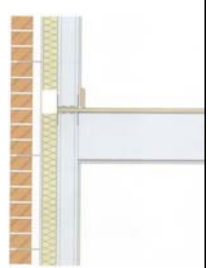
Reference No.	Reference RD	‘as designed’	‘as built’	Description	Examined for risk to:	*TDR (highlighted if above 0.25*[3])*	Comments on the ‘as built’ case
01	3.12			It was observed that, in some ‘as built’ cases, some insulation was not present. The exact amount varied but for modelling purposes ‘gaps’ of approximately, 170 mm, and 260 mm in height were assumed. (Note that the 260 mm gap extended to below the scope of the diagram).	SURFACE CONDENSATION	$TDR_d = 0.075$ $TDR_b = 0.200$	A significant reduction in the surface temperature of the as built case is observed however no RH above 80 % was predicted.
02*	3.12			In this ‘as built’ case, cavities were closed vertically at doors using plastic proprietary closers with no expanded polystyrene or any another insulation provided. The air gap width is 80 mm.	SURFACE CONDENSATION	$TDR_d = 0.300$ $TDR_b = 0.430$	This already cold design is made even colder by the missing insulation and is significantly above the 0.25 recommendations of BS 5250. It has a maximum predicted RH of 98% and will be colder than glazing.

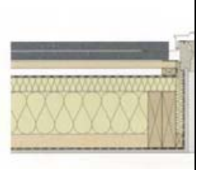
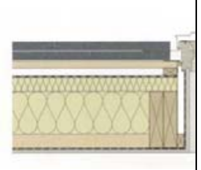
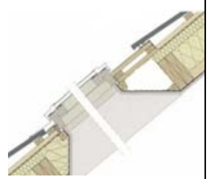
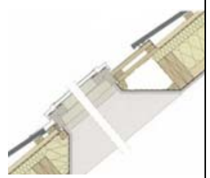
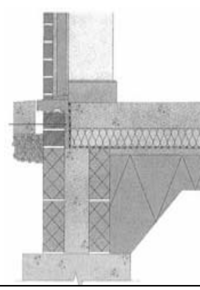
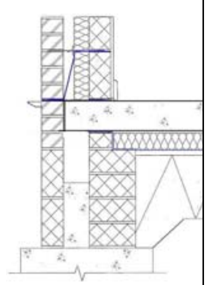
* BS5250 recommends that “A surface temperature factor of not less than 0.75 is considered to be sufficient to avoid mould growth, given the range of conditions in UK buildings and the UK climate”. Thus to avoid mould growth a TDR of less than 0.25 is required.

03	4.14			There is no insulation around the edge of ground floor reinforced concrete slab (as shown)	SURFACE CONDENSATION	$TDR_d = 0.125$ $TDR_b = 0.295$	Although calculations show no risk of surface condensation for the given conditions, the 'as built' TDR is greater than 0.25. Surface RHs of above 80% were predicted.
04	4.14			There is no insulation around the edge of ground floor reinforced concrete slab. No insulation was placed below the cavity tray (as shown)	SURFACE CONDENSATION	$TDR_d = 0.125$ $TDR_b = 0.225$	Calculations show no risk of surface condensation for the given conditions. Surface RHs of above 80% were not, predicted.
05	4.14			No insulation was placed below the cavity tray (as shown).	INTERSTITIAL CONDENSATION	-	The condensate accumulates in the period from December until February. It dries out in the period from March to April, and as such is in compliance with BS 13788: 2001.
06	6.12			Concrete slab not laid perfectly forming gaps (up to 30 mm) under the timber frame.	SURFACE CONDENSATION	$TDR_d = 0.150$ $TDR_b = 0.325$	Although calculations show no risk of surface condensation for the given conditions, the 'as built' TDR is greater than 0.25. Surface RHs of above 80% were predicted.

07	6.12			The ground floor concrete slab extends over the supporting block work forming gaps (up to 30 mm) under the timber frame, but it was observed that the slab edge insulation was filling the full depth of the cavity.	SURFACE CONDENSATION	*$TDR_d = 0.15$* *$TDR_b = 0.245$*	Although calculations show no risk of surface condensation for the given conditions, surface RHs of above 80% were predicted.
08	6.12			The ground floor slab extends over the supporting brickwork. The edge insulation is provided inside the cavity.	SURFACE CONDENSATION	*$TDR_d = 0.15$* *$TDR_b = 0.270$*	Although calculations show no risk of surface condensation for the given conditions, the 'as built' TDR is greater than 0.25. Surface RHs of above 80% were predicted.
09	6.12			The ground floor concrete slab extends over the supporting block work forming gaps (up to 30 mm) under the timber frame. The vapour control layer *was* in place.	INTERSTITIAL CONDENSATION	-	In the 'as built' case condensate accumulates in the period from December until February. It dries out in the period from March to April, and as such is in compliance with BS 13788: 2002. The risk of degradation of building materials should be considered.

10	6.12			The ground floor concrete slab extends over the supporting block work forming gaps (up to 30 mm) under the timber frame. The vapour control layer *was not* in place.	INTERSTITIAL CONDENSATION	-	In the 'as built' case condensate accumulates in the period from November until April. It dries out in the period from April to July, and as such is in compliance with BS 13788: 2002. The risk of degradation of building materials should be considered.
11	6.18			The use of multiple wall plates directly below and above intermediate floor was observed. There is no insulation in the void between the two outermost joists running parallel with external wall.	SURFACE CONDENSATION	$TDR_d = 0.220$ $TDR_b = 0.250$	Although calculations show no risk of surface condensation for the given conditions, the 'as built' TDR is equal to 0.25. Surface RHs of 80% were predicted.
12	6.18			There is no insulation in the void between the two outermost joists running parallel with external wall. Plaster board was not properly aligned with intermediate floor.	SURFACE CONDENSATION	$TDR_d = 0.220$ $TDR_b = 0.295$	Although calculations show no risk of surface condensation for the given conditions, the 'as built' TDR is greater than 0.25. Surface RHs of above 80% were predicted.

13	6.18			There is no insulation in the void between the two outermost joists running parallel with the external wall.	INTERSTITIAL CONDENSATION	-	In the 'as built' case a condensate accumulates in the period from November until March. It dries out in the period from April to July, and as such is in compliance with BS 13788: 2002. The risk of degradation of building materials such as wood might be expected.
14	6.19			Missing insulation in corner of a wooden framed wall.	SURFACE CONDENSATION	TDR_d = 0.278 TDR_b= 0.394	Although calculations show no risk of surface condensation for the given conditions, the 'as built' TDR is greater than 0.25. Surface RHs of above 80% were predicted.
15	7.13			The gap between insulation sheets fitted to the external side of the steel frame is shown in the 'as built' case of the Robust Detail. It indicates how the floor cassette is fixed to the lower steel panel and it varies from 40mm to less than 10mm.	INTERSTITIAL CONDENSATION	-	Condensate dries out in the period from April to June, and as such is in compliance with BS 13788: 2001.A vapour control layer is necessary on the warm side of the insulation to reduce the risk of damaging interstitial condensation on the inner surface of sheathing board. Additionally, high humidity might cause corrosion of the steel frame.

16*	8.03			Insulation inside reveals and trimmers is missing.	SURFACE CONDENSATION	TDR_d = 0.350 TDR_b= 0.440	Although calculations show no risk of surface condensation for the given conditions, the 'as built' TDR is greater than 0.25. Surface RHs of above 80% were predicted.
17	8.03			Although the insulation was in place around the rooflight sills, it is questionable as to whether any insulation was in place inside the reveals as illustrated in the 'as built' case of the Robust detail.	INTERSTITIAL CONDENSATION	-	The water content calculations in both 'as designed' and 'as built' cases predict only a negligible condensation.
18	8.03			The same as in the previous case **except that the vapour control layer is missing**.	INTERSTITIAL CONDENSATION		The water content distribution is much higher when the vapour control layer was not in place. Although condensate dries out during the year, the high condensate content might be damaging to materials.
19	8.06			Note that often the ground floor slab extends to the outer brick work. Note: The results described here refer to a section just to one side of the threshold.	SURFACE CONDENSATION	TDR_d = 0.195 TDR_b= 0.370	Although calculations show no risk of surface condensation for the given conditions, the 'as built' TDR is greater than 0.25. Surface RHs of above 80% were predicted.

*Note that the lowest thermal bridge temperature used was calculated for the computational cell adjacent to the window frame.

47. Although no surface condensation risk is predicted for the ‘standard’ constructions, 10 out of 12 ‘as built’ RCDs failed to meet the standard requirements regarding mould growth.

48. The ‘as built’ RCDs all passed the drying out requirements given in the standard regarding interstitial condensation. However, in 4 out of 7 cases some condensation is predicted at times when none is predicted for the ‘as designed’ RCDs.

49. The amount of condensate that would cause significant degradation of a building material in a particular situation is not standardised. Although the predicted amounts of condensate dry out and as such are in compliance with BS EN ISO 13788, the risk of degradation of building materials and deterioration of thermal performance as a consequence of the calculated maximum amount of moisture should be considered.

50. It is evident that the influence of workmanship on moisture performance exists, and in many cases has a significant effect on degrading the hygrothermal performance of ‘as designed’ robust details. For more detailed modelling results see Appendix 11.

Part 5: Investigation of the potential impact of selected factors on condensation risk in robust details and in typical UK dwellings

51. This part of the report investigates the potential impact of extreme behaviour in terms of moisture generation, ventilation and heat transfer on condensation and mould growth risk of five selected ‘as built’ RCDs. In addition, this task includes a sensitivity analysis of selected ‘as built’ RCDs.

52. The work presented in this section is divided into four subsections:

- The effect of excessive moisture generation on condensation risk and mould growth.
- Assessing the influence of workmanship on condensation risk and mould growth in typical UK dwellings.
- The effect of different surface heat transfer coefficients on the risk of condensation and mould growth.
- Sensitivity analysis of different ‘as built’ RCDs.

53. A subset of five ‘standard’ and ‘as built’ ‘most at risk’ RCDs was selected and further analysed in this part of the project. For a detailed description of the selected robust details see Appendix 12.

54. Using the ‘Warm Front’ database of dwellings, the top 5% of excess vapour pressures was determined which may be considered to represent ‘extreme’ occupant behaviour. The highest 5% of bedrooms had a vapour pressure excess greater than 700Pa (normalised at 5 °C). The highest 5% of living rooms had a vapour pressures excess greater than 625 Pa (normalised at 5 °C). There is no evidence to suggest that the houses with extremes of vapour pressure excess had high occupant density or were particularly air tight.

55. Using the top 5% of excess vapour pressures in bedrooms, a surface RH was calculated, as prescribed in Annex B.1 of BS EN ISO 13788. Comparisons of surface condensation modelling results for the ‘standard’ and ‘as built’ RCDs for extreme vapour pressure excess are presented in Table 1 in Appendix 12.

56. Note that values of the vapour pressure excess recommended in the Standard are at the upper limit value for the class 3 (dwellings with low occupancy, as in BS EN ISO 5250) i.e. a relatively high value. Therefore, the impact of extreme occupant behaviour in the modelling undertaken for this study (using the ‘extreme’ values from the Warm Front study) is not dramatic. However, in cases where the effect of workmanship already had been shown to cause a significant increase in the maximum predicted RH, e.g. for RCD 6.19 (Timber Frame. Wall Junction), the extreme moisture loading is more likely to lead to potentially damaging condensation.

57. Note that the mean infiltration rate measured in the Warm Front study was 0.72 ach^{-1} which is above the generally accepted minimum level of 0.5 ach^{-1}. As vapour pressure excess is determined by both moisture generation and the air change rate, one might expect higher vapour pressure excesses in ‘tighter’ dwellings. Furthermore, the Warm Front data set applies to the elderly and young families on income support and as such it may not be typical of the wider population – this requires further analysis.

58. With regard to interstitial condensation risk, according to BS EN ISO 5250, any interstitial condensation that occurs within a structure in the winter should evaporate during the summer to prevent an accumulation from year to year. Whilst for a ‘standard’ vapour pressure excess the ‘as built’ RCD 7.13 (Lightweight intermediate floor - steel frame) passed this test, in the case of ‘extreme’ occupant behaviour the condensate does not dry out during the summer months.

59. With regard to surface condensation risk, a nomogram has been developed using ‘Condensation Targeter’ to quantify the effect of workmanship on thermal performance of both ‘standard’ and ‘as built’ RCDs. The fitted curves, linking the surface RH with the air change rate, moisture generation and TDR were derived using the modelling results from 54 simulations (see Figure 3).

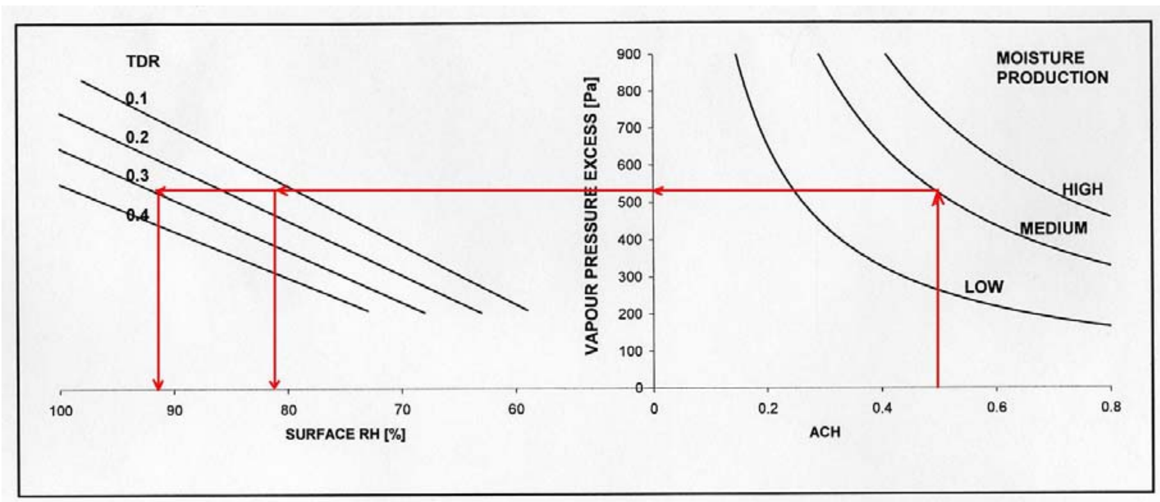


Figure 3. A nomogram designed to quantify the influence of workmanship on the condensation risk. Note that this diagram is derived using the mean January temperature for the London region (3.7 °C).

60. Note that for the vapour pressure excess predicted by ‘Condensation Targeter’ and given in the nomogram, two out of the four ‘most at risk’ ‘as built’ construction details would fail the standard requirements related to surface condensation risk. If high moisture production was assumed, i.e. ‘wet’ occupancy, three out of four details would fail the requirements concerning surface condensation risk.

61. It appears that the influence of workmanship on the moisture performance of the robust details can be significant in cases of elevated moisture generation in dwellings.

62. The impact of furniture layout on the risk of condensation and mould growth was investigated by varying the convective heat transfer coefficient. Note that a wide range of different values for convective heat transfer coefficients have been reported, varying from 0.5 to 7.0 W/m^2K for walls. However, most of these values have been obtained using small free edged heated plates and not taking into account complex air movement patterns found in real buildings.

63. The literature indicated that the following values would represent a reasonable range of the convective heat transfer coefficients which could occur behind furniture for vertical walls; 2, 2.5 and 3.0 W/m^2K, for ΔT = 5 °C. These values were thus used in this sensitivity study. Note that the ‘standard’ value that had been used for the ‘standard’ runs was 4.0 W/m^2K. Accurate values of the convective heat transfer coefficients are of paramount importance in order to be able to predict the performance of robust details, not just concerning condensation risk and mould growth, but also with regard to energy consumption and thermal comfort predictions.

64. The results of the modelling work emphasise then that the performance of the robust details is significantly sensitive to the value of the convective heat transfer coefficient. It appears that the predicted effect of furniture placed close to an external wall can be to increase the surface RH by the order of 10%.

65. Sensitivity analysis for different 'as built' RCDs has also been undertaken. This additional work, over and beyond that required by the original proposal, investigated the sensitivity of the modelling work to various issues.

66. To analyse the effect of different type of blocks and gaps in insulation on condensation risk and mould growth in window jambs and sills, RCD 3.12 was selected. Two types of blocks have been selected with thermal conductivities of 0.5 and 0.7 W/mK. In addition, different gaps have been modelled, namely 25, 100 and 250 mm.

67. The surface RH was calculated assuming the internal temperature of 20 °C and an internal RH of 50%. Note that the missing insulation is a significant issue, as the surface temperature decreases with increasing gap size. RCD 3.12 is not however, very sensitive to changes in thermal properties of selected blocks.

68. The effect of different insulation types, namely mineral fibre and polyurethane, on the likelihood of interstitial condensation, was investigated using RCD 4.14. Differences between the mineral fibre and polyurethane insulation boards (both with no vapour control layer (VCL) in place) were noted. However, the most significant difference was observed when the VCLs were applied to the polyurethane as might be expected 'in the field'. The performance with the VCLs was significantly improved.

69. The importance of the VCL in a rooflight was also investigated. The water content distribution was much higher when the vapour control layer was not in place. Although condensate dries out during the year, high levels of condensate might be damaging. The condensate formed between three different layers of the construction.

70. In summary then, it appears that the potential impact of the occupier on moisture generation can be significant. Sensitivity analysis for selected 'as built' construction details has also been undertaken and highlighted some important issues.

Workshop (Milestone 12)

71. Milestone 12 has been completed. The workshop was held at University College London on 27th April 2005 to disseminate the results of the project and to seek feedback from the 18 external attendees (27 in total including attendees from academia and the research teams). See Appendix 13 for list of attendees. The main aim of the workshop was to present the results of the research to industry and obtain feedback on the conclusions which could both help interpret the results and provide a 'reality check' on the work.

72. The main issues that arose from discussions at the workshop are briefly summarised below. The summary does not necessarily represent a consensus position – rather a record of the points that were raised. At no stage during the workshop did it appear as if the results of the research were at variance with the practical experience of the industry. The main discussion focused around practical solutions to detailing problems and how to motivate the industry to implement RCDs. For example:

- Why have the Part E robust details which relate to acoustics permeated peoples consciousness but not those relating to hygrothermal performance i.e. Part L? Is this due to the threat of testing which occurs with part E but not with part L? Testing should take place for Part L, e.g. infra-red testing etc.
- Part E is 'industry led' – subscription to a formal scheme is required therefore people know about it. Should the same kind of thing happen with Part L?
- RCDs should/could be modified to accommodate 'real workmanship'. At present some of the details which appear in the RCDs are purely theoretical and could never be constructed in practice. If industry is to take the RCDs seriously they must feel that they can construct the details as drawn.
- Building components which can facilitate better construction of robust details should be looked at with urgency – the component industry should be alerted, challenged and motivated to solve the

real on-site problems of construction to RCDs. Something like ‘Eurogroove’ – may also generate compatibility between components –standardisation of components. Too many manufacturers are ‘doing their own thing’.

- Transfer of knowledge to site is vital if RCDs are to be effective - simply producing a set of ‘pictures’ is not enough. Site workers should be educated as to how to achieve robust details in practice. In addition, real problems which occur on site will always mean that there are occasions where it is not possible to construct on site to RCDs in such situations it is important that site workers understand what RCDs are trying to achieve in order to achieve an appropriate solution. It is therefore vital to build in a ***process*** to RCD education/prescription.
- Tolerances are a key factor – this was an issue that also arose in the first project workshop. For example, how to accommodate deviations in floors in RCDs? There is a conflict with the fact that some deviation is allowed in the British Standard but the RCDs do not demonstrate how this can be accommodated in practice.
- Do RCDs stifle creativity? How can the development of novel and effective details be encouraged?
- It was suggested that perhaps structural engineers should take responsibility for RCDs because they have relevant training and an interest in ‘detail’ and hence are strongly placed to take a lead on this issue.

Suggestions for further work

73. The fieldwork sites should be re-visited to investigate how houses with the identified ‘faults’ are performing. The houses should be studied with regards to mould growth, an IR survey, temperature, RH and pressure testing. This work would have two objectives:

- To test the validity of the theoretical modelling work which is used to construct robust details
- To provide the hard evidence to the construction industry of the impact that not adhering to RCDs has, e.g. through IR images, pictures of mould etc..

74. The research so far undertaken provides a unique opportunity to undertake this work with minimal cost, as the most expensive tasks have been already completed, i.e. data collection to determine sites which have been constructed incorrectly and the initial theoretical modelling work has already been undertaken. To complete the work an extensive hygrothermal survey will need to be undertaken comprising of:

- Fan pressurisation testing to measure the air tightness of the houses
- IR surveys during pressurisation to identify the location of air leakage paths
- IR surveys to determine the degree of cold bridging compared to thermal models
- Measurement of air and surface temperature and RH in the ‘problematic’ room of each house, and externally, over a period of 4 weeks to assess the resulting hygrothermal conditions in the property.
- Questionnaire survey to establish occupancy and moisture production in the dwelling
- Inspection and survey to look for condensation, damp and mould
- Additional modelling work using real boundary conditions

75. A protocol for the testing of RCD compliance should be investigated. It is clear that the industry only takes an issue seriously when it feels it will be tested and potentially forced to ‘make good’. Acoustic testing is already achieving this - it is therefore essential that such a test procedure is developed for hygrothermal RCDs. The results from the work specified in paragraph 72 should make it possible to start to develop such a test.

76. There are fire/sound issues resulting from the work that has been carried out – workers in these fields should look at what was discovered and report on the implications.

Dissemination

77. It is proposed that further dissemination will take place via conventional academic journals but also, importantly, via other routes such as trade publications. The following academic papers are in the process of being prepared or have already been submitted:

- M. Bell, M. Smith, D. Miles-Shenton, M. Davies, T. Oreszczyn, D. Mumovic, I. Ridley (2006) Detail design, construction quality and condensation performance in house construction; to be submitted for publication in a special issue of Structural Survey; Title of issue: Building Operational Performance
- D. Mumovic, I. Ridley, T. Oreszczyn, M. Davies (2005) Condensation risk: comparison of steady-state and transient methods; submitted to Building Services Engineering Research & Technology (BSERT)
- D. Mumovic, M. Davies, I. Ridley, T. Oreszczyn, M. Bell, M. Smith, D. Miles-Shenton (2005) An evaluation of the hygrothermal performance of 'standard' and 'as built' construction details using steady state and transient modelling; 9th International Building Performance Simulation Association (IBPSA) Conference; 15-18 August; Montreal, Canada.

78. In addition it is recommended that a dissemination plan is developed and implemented for the non-academic community.

Discussion and Conclusions

79. Providing details which are hygrothermally robust is critical to the achieving energy efficient, healthy and comfortable buildings with minimal fabric deterioration. The research presented in this report has demonstrated that although there are very good examples of detailing, in most cases there is very little attention paid to many of the details. The main reason is that there is little knowledge of the importance of the details. In part this is thought to be because there is no real knowledge about why they are important or what they are trying to achieve. There is also a lack of any real enforcement or the requirement for remedial work where incorrect details have been constructed. In part this is because properties have not been air-tight and U-values relatively high i.e. there has been a considerable safety margin in their construction before they fail. However as U-values progressively decrease and air-infiltration is reduced the impact of incorrect construction of RCDs will increase. In effect, we have to ventilate our properties (for example in the case of RCD 4.14) by an extra 0.15 ach^{-1} to accommodate/prevent mould growth etc, at poorly constructed robust details. This results in an energy penalty.

80. The findings of the fieldwork suggest that the house construction industry is not able to produce, with any degree of consistency, construction that is well designed and achieves the performance required of robust construction. The failure is not a question of one or two developers and their subcontractors making errors but a failure at the systems level, involving the whole industry including developer, designer, constructor, regulator and materials & component suppliers.

81. The study of the use of RCDs reinforces the need to rethink the details themselves, the way they are presented and to review the way they are applied in practice. This will require a concerted effort on the part of regulators, designers, constructors and the industry as a whole. The principles on which details are based and key performance characteristics need to be clearly articulated for all details. Advice is needed on how to interpret and translate the "book details" into real constructions and on how to extend the principles to cover non-standard situations. Training is required at all points in the process so that all those involved understand the importance of the performance characteristics and what elements of the details are critical. To rely on a "copy the picture in the book" approach is unlikely to be successful since there is rarely a simple one to one correspondence between the picture and the real object.

82. For the RCDs modelled, simple (current) methods give good agreement with more complex methods provided that either driving rain is not an issue or that the internal conditions are not subject to severe transients. When the fabric is subject to these conditions, the complex models differ significantly from the simple methods.

83. It is evident that the influence of workmanship on moisture performance exists, and can have a significant effect on degrading the hygrothermal performance of 'as built' robust details.

84. Although no surface condensation risk is predicted for the given conditions, 10 out of 12 ‘as built’ details failed to meet the standard requirements regarding mould growth.

85. The ‘as built’ details passed the drying out requirements given in the standard regarding interstitial condensation. However, in 4 out of 7 cases some condensation is predicted at times when none is predicted for the ‘as designed’ robust details. The risk of degradation of building materials and deterioration of thermal performance as a consequence of the calculated maximum amount of moisture should be considered.

86. With regard to interstitial condensation risk, according to BS EN ISO 5250, any interstitial condensation that occurs within a structure in the winter should all evaporate during the summer to prevent an accumulation from year to year. Whilst for a ‘standard’ vapour pressure excess the ‘as built’ RCD 7.13 (Lightweight intermediate floor - steel frame) passed this test, in the case of ‘extreme’ occupant behaviour the condensate does not dry out during the summer months.

87. With regard to surface condensation risk, a nomogram has been developed using ‘Condensation Targeter’ to quantify the effect of workmanship on thermal performance of both ‘standard’ and ‘as built’ RCDs. Note that for the vapour pressure excess predicted by ‘Condensation Targeter’ and given in the nomogram, two out of the four ‘most at risk’ ‘as built’ construction details would fail the standard requirements related to surface condensation risk. If high moisture production was assumed, i.e. ‘wet’ occupancy, three out of four details would fail the requirements concerning surface condensation risk.

88. The results of the modelling work emphasise then that the performance of the robust details is significantly sensitive to the value of the convective heat transfer coefficient. It can be seen that the predicted effect of furniture placed close to an external wall can be to increase the surface RH by the order of 10%. In summary then, it appears that the potential impact of the occupier on moisture generation can be significant. Sensitivity analysis for selected ‘as built’ construction details has also been undertaken and highlighted the criticality of issues such as avoiding gaps (even relatively small ones) in insulation and the maintenance of vapour & air control layers.

References

BSI (1996) BS EN ISO 10211-1:1996 Thermal bridges in building construction – Calculation of heat flows and surface temperatures, BSi, London

BSI (2001) BS EN ISO 13788:2001 Hygrothermal performance of building components and building elements - Internal surface temperature to avoid critical surface humidity and interstitial condensation - Calculation methods, BSI, London

BSI (2002) BS5250:2002 Code of practice for the control of condensation in buildings, BSi, London

DEFRA and DTLR (2001) Limiting thermal bridging and air leakage: Robust construction details for dwellings and similar buildings. London. TSO.

List of Appendices

1. A Project Proposal to ODPM Building Regulation Division. Project Reference Number: CI 71/6/1 BD2414
2. C1:M1 Interim Report: Initial workshop & site selection criteria
3. C1:M2 Interim Report: Site descriptions & review of initial modelling
4. C1:M2 Surface Appendix A1
5. C1:M2 Interstitial Appendix B1
6. C1:M3 Interim Report: Comparison simple vs. complex methods
7. C1:M3 Surface Appendix A1
8. C1:M3 Interstitial Appendix B
9. C1:M7 Interim Report: Final report on project fieldwork
10. C1:M8 Interim Report: An evaluation of hygrothermal performance of the 'standard' and 'as built' construction details
11. C1:M8 Appendix 1
12. C1:M9 Interim Report: Risk of condensation
13. C1: M12 Final workshop – list of attendees