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RC框架结构地震破坏机理与抗倒塌研究 现状与展望*

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摘要: 多层钢筋混凝土(RC)框架结构地震破坏机理与抗倒塌设计理论一直是地震工程领域的研究热点。聚焦砌体填充墙对结构破坏模式的影响,从地震倒塌机理、结构破坏模式与成因剖析、抗地震倒塌设计理念3个方面对国内外开展的多层RC框架结构抗震研究进行了梳理、总结。结果表明:地震作用下实际工程及实验室模型难以出现设计预期的“强柱弱梁”破坏,设计细节和非结构构件均影响结构的地震破坏模式;改善填充墙与周围框架连接方式、增设翼墙或设置柔性填充墙一般均能保证结构的抗倒塌性能。

关键词: RC框架结构; 破坏模式; 抗倒塌; 砌体填充墙; 翼墙

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Progress and Prospect on Seismic Collapse Mechanism and Collapse-resistant Capacity of RC Frame Structures

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Abstract: Multi-storey RC frame has been applied widely because of its flexible layout and economic applicability. Due to the complex behavior of materials and influence on nonstructural components, there is still no generally rational method for predicting the seismic failure mode and evaluating the anti-collapse capacity of RC frame structures. In the past decades, based on the seismic analysis, model tests and FE simulation, massive amount of studies have been carried out to investigate the seismic failure mode and collapse mechanism of RC frame. This paper summarizes these studies from the following aspects: the failure mode and collapse mechanism, the yielding mechanism and the anti-collapse design theories. Furthermore, the latest research progress is presented, the existing problems are pointed out and the research trends are prospected.

Keywords: RC frame; seismic failure mode; collapse resistant; masonry infills; structural walls

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引言

多层RC框架结构因其平面布置灵活、经济适用、建造方便等优点,在世界各国广泛应用,但此类建筑抗震表现不甚理想。以汶川地震为例,震害调查结果表明极震区内多层RC框架结构倒塌指数甚至高于多层砌体结构^[1],这与多层RC框架结构抗震性能的传统认识有较大差异。按现行抗震设计规范“强柱弱梁”原则设计的多层RC框架结构,抗震表现同样不能完全符合设计预期,实际震害形态仍以“柱铰屈服破坏”或“剪压脆性破坏”为主。因此,科学认识多层RC框架结构地震破坏模式,在此基础上发展考虑非结构构件影响的抗震性能提升策略与设计方法,对保障结构的地震安全至关重要。

本文从地震倒塌机理、结构破坏模式与成因剖析、抗地震倒塌设计理念3个方面对多层RC框架结构地震破坏模式的研究脉络进行梳理、凝练,介绍了相关研究成果,同时对多层RC框架结构抗震研究发展趋势进行了展望。

1 RC框架结构地震倒塌机理

1.1 结构地震倒塌评判准则

历史震例表明,结构倒塌是地震造成人员伤亡和设备损毁的最主要原因。随着新型传媒的发展,震后现场的断壁残垣给人们带来的视觉冲击更为强烈,使得社会对建筑物抗倒塌问题更为关注。如何避免结构地震倒塌是亟待解决的社会问题和科学问题,也一直是地震工程界的研究热点与难点。

探讨结构地震倒塌问题时,倒塌评判准则的科学性至关重要。20世纪60年代,G. W. Housner^[2]提出了反映变形与应力变化的能量破坏准则,即荷载作用下构件累积的形变能超过自身耗能限值时判定构件失效。N. K. Gosain等^[3]将能量法判别原则引入到钢筋混凝土构件抗剪承载力验算,D. Darwin等^[4]、Y. J. Park等^[5]也基于该方法开展了系列的研究。然而,由于钢筋混凝土材料的复杂性,且评价准则没有考虑结构形式和材料的差异性,因此应用能量破坏准则对钢筋混凝土构件破坏与结构失效评价存在一定的局限性。

张雷明等^[6]结合实际震害,在宏观尺度定义了

结构的倒塌时刻,指出RC框架结构完全形成“铰机构”倒塌实例较少,多数情况下结构倒塌出现在某些柱、梁构件的脆性破坏之后。这种关于倒塌评价准则的描述,将框架结构倒塌成因从“柱铰机制”延性破坏拓宽到了“柱铰”“梁铰”及以压剪破坏为代表的脆性破坏范畴,更加准确的定义了RC框架结构的地震倒塌标志。M. S. Lodhi等^[7]、H. Sezen等^[8-10]从位移角度研究了RC框架结构的极限倒塌问题,建立了考虑弯曲、剪切、轴压相互作用的框架柱极限位移计算方法,同时指出截面受抗剪承载力 V_n 与极限抗弯承载力对应时刻水平推力 V_p 的比值影响柱的破坏模式与延性(图1)。地震作用下,竖向承重构件的脆性破坏同样可以诱发RC框架结构的倒塌,K. J. Elwood等^[11]、L. Zhu^[12]建立了钢筋混凝土柱压剪计算方法,在此基础上发展了相应的计算模型(图2),明确了发生脆性破坏时柱极限位移值,进一步丰富RC框架结构地震倒塌评价方法。

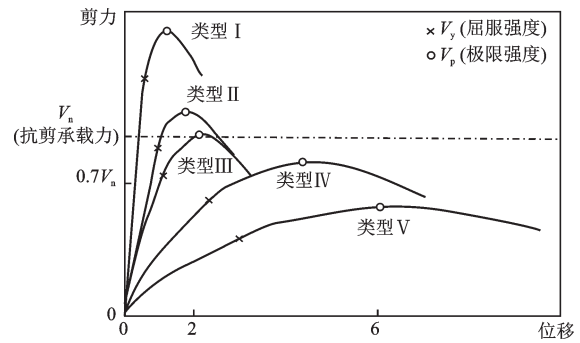


图1 抗剪承载力与极限承载力比值对延性的影响^[7]

Fig.1 The influence of V_n/V_p on displacement ductility^[7]

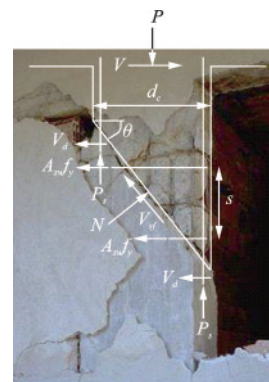


图2 框架柱压剪破坏计算模型^[13]

Fig.2 Free body diagram of column after shear failure^[13]

1.2 基于实际震害的RC框架结构倒塌机理启示

归纳、总结建筑物地震表现,反思震损建筑震

害成因,对揭示结构地震破坏机理与推动抗倒塌设计理论发展大有裨益。汶川地震后,国内学者针对多层 RC 框架结构抗震性能问题开展了系统研究^[14-23],进一步加深了对此类结构地震破坏模式与倒塌机理的认识。

郭迅^[24]统计了汶川地震极震区内典型多层结构的震损情况,结果显示极震区多层 RC 框架结构倒塌比率高于多层砖混结构(图 3),这一现象表明框架结构应对极罕遇地震的抗倒塌能力储备不足。叶列平等^[25]剖析了汶川地震中 RC 框架结构“强梁弱柱”破坏模式产生原因,认为楼板加强作用、梁端钢筋超配、非结构构件影响等是结构未出现“强柱弱梁”破坏模式的主要原因。李碧雄^[26]研究了砌体填充墙对 RC 框架结构地震破坏机理的影响,指出存在有效连接的框架-填充墙在地震作用下大概率以组合体形式共同工作,框架柱呈现“弱剪力墙”式破坏,此外墙体的存在可使柱成为短柱(图 4)、极短柱(图 5),在影响竖向构件地震力分配的同时改变结构的破坏模式(图 6)。

基于上述研究成果,多层 RC 框架结构抗震问题大致可分为以下 3 个方面:(1)极罕遇地震下结构抗倒塌冗余度问题;(2)结构地震破坏模式与成因

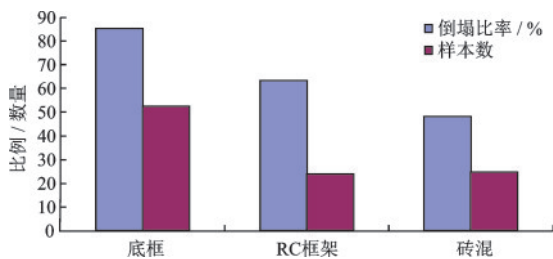


图 3 北川极震区不同类型房屋倒塌比率统计^[24]

Fig.3 Collapse ratio of structures in meizoseismal area of Wenchuan Earthquake^[24]

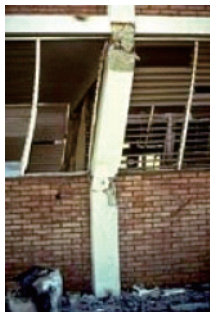


图 4 半高填充墙改变柱受力模式加剧破坏^[27]

Fig.4 Captive column restrained by partial-height masonry infill^[27]



图 5 洞口设置不当使得柱发生短柱破坏

Fig.5 Short column damage caused by improper setting of openings



图 6 填充墙的存在造成柱端剪压破坏

Fig.6 Short column damage caused by infills

问题;(3)结构抗倒塌设计方法问题。

1.3 框架结构地震倒塌问题研究

我国现阶段主要基于“三水准、两阶段”中“小震不坏”进行结构线弹性阶段的抗震设计,结构抗倒塌验算是间接的,未明确给出结构抗倒塌的定量计算方法和评价指标,因此按照同一规范设计不同地区、不同结构的抗地震倒塌能力会有较大差异^[28]。汶川地震的惨重灾害引起关于工程结构抗震设防和抗震设计目标的广泛讨论和反思,基于未来地震规模的极不确定性以及地震中地震烈度往往远超设防烈度的事实,有必要改进现有的抗震设防策略以平衡结构安全性需求,即开展结构抗地震倒塌定量设计方法及极罕遇地震下结构抗倒塌能力评价的研究^[29]。叶列平等^[30]基于建筑物震害表现提出了建筑结构安全储备应具备基本安全储备、整体安全储备、意外安全储备三个层次,这一观点与张敏政^[29]提出的“强地震动发生具有很强的不确定性,结构抗震设计应更加注重概念清晰”理念不谋而合。国内学者^[31-36]在不考虑填充墙等非结构构件的影响下探讨了框架结构在极罕遇地震下的抗倒塌性能,并尝试建立了不同抗震设防等级下的结

构地震易损性曲线。

2 RC 框架结构地震破坏模式影响因素研究

2.1 RC 框架结构地震破坏模式

(1) 框架结构屈服机制研究

地震作用下,钢筋混凝土框架结构大致出现梁端塑性铰、柱端塑性铰、压剪以及拉剪等破坏形态。H. Takizawa 等^[37]研究了延性框架结构的地震失效模式,分析了考虑 P-delta 效应的框架结构开裂、屈服、刚度退化及倒塌等问题,描绘了延性框架的破坏全过程。K. J. Elwood 等^[38]借助振动台试验及 OpenSees 研究了考虑轴力与剪力共同作用下钢筋混凝土框架结构倒塌问题,建立了用于评估 RC 框架结构极限倒塌问题的倒塌临界模型与位移角计算公式。Y. Harumi 等^[39]通过模型试验分析了短柱(剪跨比 1.5)剪切破坏过程,指出受剪失效的构件仍会伴生塑性铰破坏,但剪切破坏占主导。综上,基于“塑性铰”延性破坏模式的框架结构需同时具备轴压比适中、具有良好的配筋与配箍、避免短柱效应以及避免局部刚度过大等条件^[40],上述要求限制了延性框架结构设计目标的实现。

(2) 层屈服机制震害成因分析

A. B. Climent 等^[41]研究了采用欧洲规范建造的框架结构的抗震性能,表明裸框架结构表现出符合设计预期的抗震性能与破坏模式。车轶等^[42]比较了中欧抗震设计规范关于“强柱弱梁”的定义,结果表明两种规范在延性设计、楼板作用、楼板配筋、轴压比限值、配箍以及填充墙构造等方面均有明显差异,欧洲规范相关要求要更严格、细致。黄华等^[43]指出填充墙、楼板对多层 RC 框架结构破坏模式的影响不容忽视,轴压比限值过高也是强梁弱柱震害出现的原因之一。王素裹等^[44]探讨了梁截面形式对“强梁弱柱”震害成因的影响,指出相同条件下宽梁更易实在梁铰屈服机制。杨红等^[45-47]研究指出即便不考虑填充墙对结构抗震性能的影响,经抗震设计的框架结构在罕遇地震下破坏模式以“柱铰机制”为主,地震动的空间作用、确保“强柱弱梁”的规定要求相对较低、结构遭遇“超烈度”强震共同导致了“柱铰机制”破坏模式的出现。

2.2 设计细节对框架结构屈服机制的影响

(1) 柱端增大系数的影响

于晓辉等^[48]探讨了柱端弯矩增大系数对框架结构失效模式的影响,指出不考虑填充墙及楼板影响时,增大系数取 3.0 以上时结构发生“强柱弱梁”破坏的概率显著增大,这一数值明显高于目前规范给出的建议值。S. C. Chun 等^[49]研究了梁、柱截面高度比值对节点破坏模式的影响,指出梁高小于柱截面宽度时,破坏模式为梁端塑性铰;梁柱截面高度比大于 2.0 时,破坏模式为节点处剪切破坏。

(2) 楼板的影响

李永梅等^[50]研究了楼板对框架结构性能的影响,指出楼板的存在导致结构延性下降、地震风险性提高的同时改变结构地震破坏模式,抗震设计时不应忽略楼板的作用。张望喜等^[51]探讨了考虑楼板对框架结构破坏模式的影响,柱端弯矩增大系数需提升至 2.0 以上时,“强柱弱梁”屈服机制才能实现;门进杰等^[52]进行了一系列带楼板翼缘的钢筋混凝土柱-钢梁组合体抗震性能试验,探讨楼板对结构抗震性能的影响,指出楼板可提高梁承载力、力矩,影响结构的地震破坏模式,并对楼板“有效翼缘宽度”进行了刻画。

(3) 配箍的影响

傅剑平等^[53]通过 19 个节点模型试验探讨了节点的破坏模式,指出箍筋水平是影响节点受力机制与破坏模式的主要因素。P. Galanis 等^[54]通过振动台对比试验研究了配箍率对框架柱地震破坏模式的影响,结果表明纵筋设置相同的情况下配箍率决定了构件的破坏形式,配箍率越高越容易发生延性破坏。C. L. Wu 等^[55]的研究同样表明相同条件下合理配箍的 RC 框架柱更易出现“塑性铰”破坏,而构造配箍不足时柱通常发生压剪破坏。邢国华等^[56]研究了多重复合箍筋对框架结构抗震性能的影响,指出复合箍筋柱表现出更优越的延性和耗能能力,同时配置复合箍筋的柱截面尺寸和轴压比等方面有优势,使得“梁铰机制”破坏模式得以实现。

(4) 轴压比的影响

刘伯权等^[57]通过三层三跨平面框架模型试验探讨了轴压比与梁柱线刚度比对框架结构破坏模式的影响,表明更小的轴压比及梁柱线刚度比会提升结构的抗倒塌能力。张喆等^[58]探讨了轴压比对

框架结构屈服机制的影响,结果表明轴压比越大,“强柱弱梁”破坏模式越难实现。需要指出的是,我国现行的抗震设计规范虽已调低了轴压比的限值,但限值仍高于欧美规范。

(5)空间作用的影响

H. Rodrigues等^[59]通过24根矩形截面钢筋混凝土柱拟静力对比试验研究了加载方向、荷载形式对柱力学性能的影响。结果表明双向荷载作用下构件的极限承载力明显下降,且达到极限承载力后的承载力下降速度明显加快,同时双向地震力作用下构件的延性会大幅降低。雷远德等^[60]设计了4组三级框架梁柱节点试件开展节点破坏机理研究,指出考虑空间作用结构更易发生破坏,且破坏形态以“柱铰”+脆性破坏为主。

2.3 填充墙对框架结构破坏模式影响研究

填充墙对框架结构抗震性能的影响不可忽视,且影响不局限于对结构动力特性、自重及刚度等方面,应重视墙体对结构整体变形模式、受力机制、关键构件/节点破坏模式的影响。

(1)基于模型试验的框架-填充墙性能研究

填充墙的存在改变了竖向构件刚度与变形能力,进而影响结构的整体性能。童岳生等^[61-62]研究了设置填充墙后的框架结构变形与承载能力,探讨了组合体变形能力与破坏形态,提出了“等效斜撑”计算模型并发展了组合体刚度计算建议公式。美国雄等^[63]基于大比例尺模型振动台试验研究了填充墙-框架工作机理及墙体对结构动力特性的影响,提出了用于周围框架-墙体初始刚度及承载力的计算方法。F. Colangelo^[64]通过框架-填充墙组合体抗震拟动力试验研究了组合体的抗震性能,指出与裸框架相比设置填充墙后组合体的平面内初始刚度和承载力的增幅不匹配,初始刚度的增量远高于承载力增量。A. Hashemi等^[65]通过振动台试验分析了填充墙对框架结构抗震性能的影响,指出填充墙的存在显著提升了柱对抗弯承载力的需求。

填充墙对框架结构抗震性能的影响,更多的是表现在对构件及结构整体破坏模式的影响上。郭子雄等^[66-67]开展了框架填充墙组合模型抗震试验,研究了填充墙不规则布置对RC框架结构抗震性能的影响,指出填充墙在明显提高结构整体刚度的同时,大幅降低结构延性并影响结构整体的破坏模

式。A. Stavridis等^[68]开展了三层单榀两跨非延性框架结构模型试验研究,指出小震下破坏主要集中在填充墙处,柱端破坏相对较轻;然而大震下框架柱并未出现预期的塑性铰破坏,而是典型的压剪破坏(图7)。郭迅^[69]开展了框架-填充墙组合体抗震性能试验研究,结果表明半高连续填充墙显著改变了竖向构件受力机制,并提出了“凝震聚力、个个击破”的多层RC框架结构地震破坏模式;S. H. Basha等^[70]的研究结果表明即便填充墙材料强度极低,框架-填充墙组合体内框架柱破坏形式仍为压剪脆性破坏。T. C. Chiou等^[71]研究了框架-填充墙共同工作机理,结果表明高宽比对组合模型承载力及墙体裂缝展布形态均有影响,同时高宽比越大组合体承载力越小。



图7 填充墙的存在使得框架柱发生压剪破坏^[68]

Fig.7 Compressive-shear failure of columns caused by masonry infill^[68]

(2)框架-填充墙性能数值分析

已有试验研究证明,框架结构中填充墙的作用主要通过墙体对角传递,既墙体可视为“等效斜撑”,因此研究墙体对框架结构影响的重点是如何更科学、准确地描述“等效斜撑”。S. V. Polyakov^[72]提出将填充墙等效为对角受压斜撑,后续演化出3个重要问题,即确定等效斜撑的宽度、数量以及相应的材料属性。M. Holmes^[73]进行了大量的数值分析和参数研究,等效斜撑宽度建议取填充墙对角线长度的三分之一;S. Stafford^[74]对一系列填充墙钢框架试验结果分析后,发现斜撑宽度可用表征填充墙与框架刚度关系的特征参数来计算;为更加真实地模拟填充墙作用,R. E. Klingner等^[75]、T. C. Liauw等^[76]、A. Saneinejad等^[77]进一步改进了等效斜撑支撑宽度的计算方法。

单根支撑杆模拟填充墙具有一定的局限性,发展双杆模型或多杆模型能更精细地描述墙体-周围

框架相互作用。T. Schmidt^[78]在考虑框架-填充墙相互作用及填充墙刚度、强度特性的基础上发展了一种双杆模型;W. W. El-Dakhkhni等^[79]基于Saneinejad的研究成果,提出了更能准确描述填充墙作用的三杆模型;J. S. Jeon等^[80]指出对于框架结构而言填充墙材料不同结构整体的抗震性能也会有较大差异,在此基础上建立了考虑框架-填充墙相互作用的非线性三连杆计算模型。F. J. Crisafulli^[81]提出采用平行双支撑杆并联一个弹塑性剪切弹簧单元组成的模型来考虑填充墙的压剪性能。

洞口的存在改变了框架-填充墙组合体的力学性能,再用简单的支撑杆模型模拟填充墙作用难以保障计算精度。模拟洞口影响方面,一种简单有效的方法是基于实体墙支撑杆宽度乘以对应的折减系数,A. J. Durrani等^[82]提出了基于洞口宽度的刚度和承载力折减系数计算公式;此外,还可以对开洞墙体进行精细化描述来模拟洞口对墙体的影响,G. Al-Chaar等^[83]、G. Buonopane等^[84]提出采用多撑杆模型模拟洞口存在造成的应力不连续效应。F. Akhoundi等^[85]研究了墙体开洞、洞口位置与形式等因素对组合体性能的影响,建立了考虑洞口影响的组合体初始刚度、承载力计算公式并提出了改进型支撑杆模型;在意识到二维纤维单元在钢筋混凝土构件动力分析中的局限性后,K. V. Spiliopoulos等^[86]提出了基于弥散固定裂缝的三维体单元并适用于非线性动力分析,对于混凝土本构仅需要输入单轴受压状态下的抗压强度,结果表明模型具有较理想的分析精度。

国内外大量学者基于上述方法或在其基础上对分析模型加以改良进而开展框架-填充墙组合体数值分析研究。叶列平等^[87]对比分析了填充墙对框架结构抗震性能的影响,指出理想状态下填充墙可以充当框架结构的第一道抗震设计防线从而减轻框架结构的抗震性能。李英民等^[88]在汶川地震震害分析基础上,设计计算模型探讨填充墙对框架结构抗震性能的影响。结果表明均匀满布填充墙对框架结构抗震性能总体有利,当墙体平、立面分布不规则时对结构抗震不利,易产生附加剪力和短柱破坏。H. Burton等^[89]探讨了填充墙对非延性框架结构倒塌临界问题的影响,指出考虑填充墙影响对评估框架结构倒塌问题至关重要,同时指出填充墙强度过高将导致框架体系出现剪

切破坏进而过早失效。A. Stavridis等^[90]在钢筋混凝土柱的网格划分中添加了水平、竖向界面单元来考虑墙体对柱的影响,刻画了墙体对柱的冲切作用而造成的柱的压剪破坏(图8)。C. H. Zhai等^[91-92]将扩展有限元方法开展钢筋混凝土框架结构抗震性能分析,能够更真实地描述构件裂缝发展及整体的失效模式。

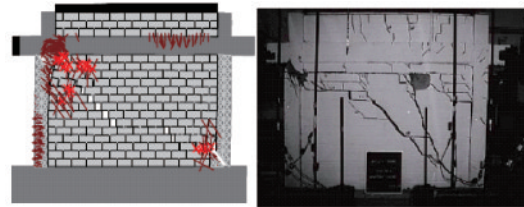


图8 框架-填充墙破坏模式数值模拟与试验结果对比^[90]
Fig.8 Deformed mesh and experimental failure pattern for RC frame with infill^[90]

3 RC 框架结构抗震性能提升策略研究

3.1 改善填充墙自身性能,降低墙体自身破坏

郭子雄等^[93]、蒋欢军^[94]等梳理了砌体填充墙框架结构抗震性能研究现状,提出了采用新型材料砌筑填充墙的抗震理念。汪裕洲等^[95]通过拟静力试验研究了再生填充墙的框架结构抗震性能。结果表明,与传统填充墙相比,框架-再生填充墙组合体变形能力及延性均有显著提升。O. Onat等^[96]通过框架-填充墙组合模型抗震试验研究了墙体出平面破坏问题,结果表明在墙体内设置水平钢筋条带可有效提高组合体的平面内强度及出平面延性,能有效抑制墙体出平面破坏的出现。

3.2 改善填充墙与周围框架接触方式

孙剑等^[97]研究了墙板与框架连接方式对抗震性能的影响,指出墙板与框架之间采用卡夹连接可以实现小震作用下墙体与框架之间柔性连接、大震下刚性连接的目标,从而提升结构抗震性能。陈晓等^[98]采用模型试验探讨了柔性连接墙板对框架结构抗震性能的影响,指出柔性连接装置有效降低了墙板刚度对周围框架的不利影响,减弱对柱的约束作用,同时有效抑制“短柱破坏”的发生。周晓洁等^[99]同样对设置预留缝的砌体填充墙框架结构进

行了试验研究(图9),结果表明柔性连接填充墙组合体延性、累积耗能性能均优于刚性连接组合体,减轻了墙体自身及结构整体的破坏程度。郭迅等在汶川地震震害现场发现边缘梁、柱外侧(图10)砌筑半高填充墙,此构造措施可有效降低上方填充墙对梁、柱的影响,为填充墙构造方式提供了新的设计理念。



图10 梁、柱上方半高填充墙采用悬挑方式与柱顶连接
Fig.10 Masonry infills located on the cantilever beams

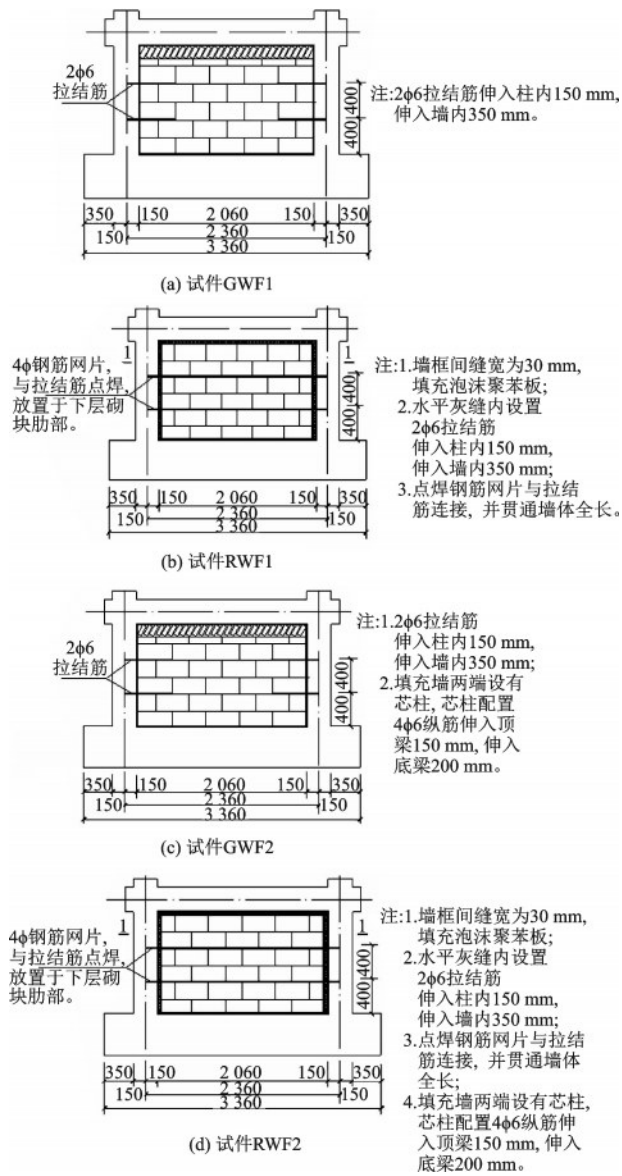


图9 填充墙柔性连接对比试验^[98-99]

Fig.9 General view of specimens for the RC frame with flexible connections^[98-99]

3.3 增设翼墙墙肢改变结构屈服机制

M. Y. Kaltakci等^[100]指出在框架结构中增设用于抵抗水平荷载的“翼墙”后,结构抗倒塌能力显著提升,同时塑性铰集中出现于梁端,实现了“强柱弱

梁”屈服机制(图11);Y. B. Li等^[101]针对框架结构节点这一抗震薄弱,提出采用钢筋混凝土翼墙进行加固(图12)并开展了抗震拟静力试验,同时探讨了翼墙形式对结构破坏模式的影响。结果表明设置翼墙能有效防止节点核心区出现破坏,同时塑性铰由柱端及节点核心区转移到梁端,实现了“强柱弱梁”破坏模式;杨伟松^[102]基于汶川地震钢筋混凝土框架结构抗震启示,针对框架结构抗倒塌薄弱环节开展了带少量“翼墙”的框架结构振动台试验研究(图13、

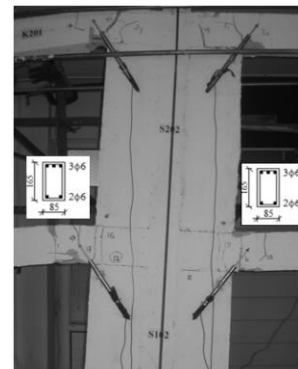


图11 框架-翼墙抗震拟静力试验^[100]

Fig.11 Pseudo-static test of RC frame with wing walls^[100]

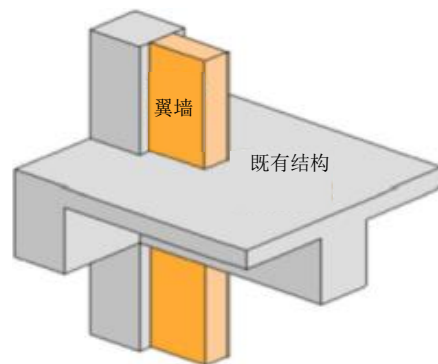


图12 框架-翼墙构造细节^[101]

Fig.12 Details of frame and wing wall joint^[101]

14), 结果表明设置“翼墙”后框架结构抗倒塌性能得到显著改善,且未出现“强梁弱柱”破坏。

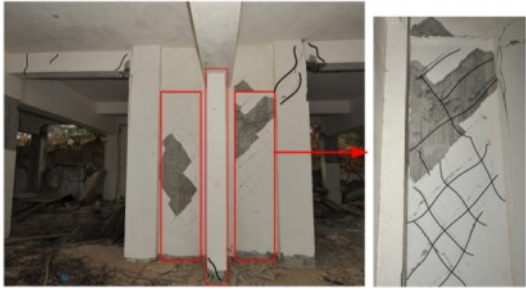


图 13 汶川地震中带少量翼墙的 RC 框架结构震害

Fig.13 Seismic damage of RC frame structure with wing walls in Wenchuan Earthquake

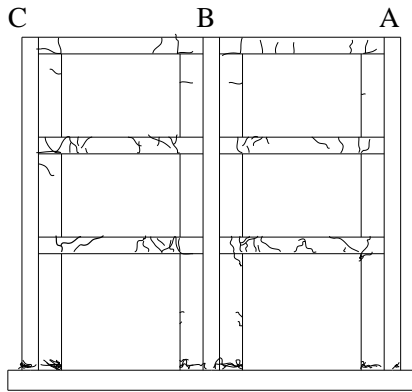


图 14 框架-翼墙结构试验破坏模式

Fig.14 Seismic failure mode of RC frame structure with wing walls

4 结论与展望

震害分析与试验研究成果已表明,按当前“强柱弱梁”原则设计的多层 RC 框架结构“梁铰机制”破坏模式仍难以实现。故而在开展 RC 框架结构地震破坏机理研究的过程中,在遵循延性设计或性能设计原则的大背景下,聚焦纯框架体系“强柱弱梁”设计原则关键参数研究的同时,应重视非结构构件对结构破坏模式的影响,尤其是填充墙对竖向构件受理机制、竖向构件破坏模式、结构整体屈服机制等方面的研究,同时有必要开展原型尺度或大比例多层多跨框架-填充墙模型地震模拟振动台试验,进一步探讨 RC 框架结构地震破坏模式与倒塌机理。

发展更加精细化的数值分析模型是研究填充墙与周围框架间相互作用的有效途径。目前需要

解决的关键科学问题是填充墙影响下框架柱的失效模式模拟,即对柱发生剪切破坏和弯曲破坏时框架-填充墙组合体性能、裂缝扩展过程中交叉与汇合以及往复荷载和动力荷载作用下裂缝开闭等问题的科学描述。

填充墙是实现 RC 框架结构建筑功能不可或缺的构件。即便结构布置合理,填充墙可以充当结构抗震的第一道防线以降低主体结构的破坏,但仍需以填充墙严重破坏为代价;不幸的是地震中更多的框架结构震害表现为设置填充墙导致主体结构发生“柱铰破坏”或脆性破坏。因而,探索一种能够发挥填充墙有利作用且规避其不利作用的方法具有重要的工程意义。现阶段已有少量的钢筋混凝土翼墙能够有效提升 RC 框架地震破坏模式,在此基础上发展“低弹模、高延性”的新型填充材料具有较好的应用前景,随着新型填充墙改进方案的不断提出和深入研究,相应的框架-柔性填充墙/框架-翼墙-柔性填充墙的抗震性能研究也将成为新的研究热点。

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